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Fakulta strojní

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OPTIMALIZACE POJEZDOVÉHO VOZÍKU A NÁVRH NOVÉHO VOZÍKU LINEÁRNÍHO VEDENÍ

Diplomová práce

2013

Technická univerzita v Liberci

Fakulta strojní Katedra výrobních systémů

Magisterský studijní program: **N2301 Strojní inženýrství**
Obor: **2302T010 Konstrukce strojů a zařízení**
Zaměření: **Obráběcí a montážní stroje**

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-
OPTIMIZATION AND DESIGN OF A NEW SPECIAL LINEAR CARRIAGE

KVS – OS – 327

Bc. Lukáš Žofka

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Počet stran: **74**
Počet obrázků: **48**
Počet tabulek: **13**
Počet příloh: **8**

V Liberci 30. 04. 2013

Originální zadání katedrou

Diplomová práce: **KVS – OS - 327**

TÉMA: **OPTIMALIZACE POJEZDOVÉHO VOZÍKU A NÁVRH NOVÉHO VOZÍKU LINEÁRNÍHO VEDENÍ**

ANOTACE:

Tato práce je rozborem návrhu konstrukční úpravy stávajícího řešení vozíku lineárního vedení v provedení ve stávajících třech variantách designu, včetně optimalizace těžiště soustavy s cílem výrazného snížení hmotnosti. Dále se zaobírá zpracováním nového konstrukčního návrhu lineárního vedení včetně konstrukce nového pojezdového vozíku se zachováním stávajícího lineárního vedení stroje a poté za použití sériově vyráběných lineárních modulů pro průmyslový stroj používaný pro výrobu nanovláken s názvem Nano Spider.

THEME: **OPTIMIZATION AND DESIGN OF A NEW SPECIAL LINEAR CARRIAGE**

ANNOTATION:

This work is an analysis of proposal for current linear carriage solution construction changes in three design alternatives including the whole assembly center of gravity optimization with the aim of significant mass reduction. Furthermore this thesis occupies the new linear guidance system construction proposal inclusive the new linear carriage design with preservation of present linear guidance system as well as by applying new ideas with help of industrially developed linear guidance modules including the carriage. This industrial machine called Nano Spider is used for nanofiber production with electrospinning technology.

Klíčová slova (Key words): TU, linear guidance system, optimization, Nano Spider

Zpracovatel (Processor): TU v Liberci, Fakulta strojní, Katedra výrobních systémů

Dokončeno (Work finished): 30. 04. 2013

Archivní označení zprávy (Archive work nomenclature):

Počet stran (Number of pages): 74

Počet příloh (Number of appendixes): 8

Počet obrázků (Number of pictures): 48

Počet tabulek (Number of tables): 13

Počet grafů (Number of charts): 0

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Datum: 30. 04. 2013

Podpis:

Acknowledgments

It is with immense gratitude that I acknowledge the support of the company Elmarco s.r.o. providing me this great opportunity to develop in deepest manner my engineering skills while accomplishing this diploma thesis and help them to further develop the importance in machine construction design.

I am indebted firstly to thank especially Ing. Josef Ferda for his professional guidance, encouragement and good advices all along. This thesis is a much work better thanks to his supervision.

My special thanks also have to go to Ing. Martin Konečný Ph.D. , who, in spite of having practically no spare time, still managed to find some time to provide me help and valuable advices in the software management and use of finite element methods. As well as I would like to express my gratitude to The Department of Textile machine design at the Technical university of Liberec providing me the important computer aided support, which gave me the opportunity to proceed freely this work I might otherwise have never encountered.

Furthermore I would like to acknowledge Ing. Petr Zelený Ph.D. for his academically lead upon this work and helping me to finalize the concept of it.

Finally, I would like to thank especially my family and friends for all their invaluable support.

CONTENTS

List of used symbols

CAD	Computed Aided Design
COG	Center Of Gravity
FEM	Finite Elements Methods
LGS	Linear Guidance System
MEMS	Micro Electro Mechanical Systems
PP	PolyPropylene
WCW	Without Counter Weight

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1 INTRODUCTION

In this work three different design tasks has to be accomplished at the first place in cooperation with researchers from the company developing the nanotechnology machine introducing the nanofibering into the industrial scale. These tasks are consisting optimization, evaluation and analysis of three different carriage designs and two different head designs in combination with assumption of fully supplied hoses with polymeric fluid being processed. The highest mass has to be considered in order to achieve the boundary conditions for the worst case in the manufacturing process. This case is arising especially at the start and end of the process trajectory of nanofibering. More specifically start of the carriage movement when the servomotor applies the tractional force or change the backwards direction. From this reason the Finite Element Methods (FEM) were applied and tasks were to revaluate the dynamic duty to the static assignment which was substituting the highest load moment in the movement and gives close result to the problematic behaviour observed in the reality and causing uneven electrospinning and linear carriage jerky movements, but was not analysed in details previously.

Nanofibers are highly engineered textiles defined as fibers with diameters less than 500 nm. Researchers around the globe are developing new uses for nanofibers in the broadest imaginable range of applications. Nanofibers often become a unique component of materials integrated deep inside of finished products. The company pursuing the unique patent in electrospinning nanotechnology aplied for machine in industrially employed technology. Work with customers and researchers demonstrate how nanofibers can benefit end products as well as to develop totally new materials or solutions to improve final product and find new applications. [1]

The nanospider technology provides an easy scale up from laboratory to industrial scale and its high volume production capability accelerates nanofiber products introduction into the market. Industrial scale applied on the linear guidance system as well as all subassemblies particularly connected with this construction is essential task of this work. Improvement of the technology results into higher production of nanofibers and recognizable improvement from the controlability point of view of the production subassebmly reserached and being improved in this work.

2 ANALYSIS OF CURRENT DESIGNS IN NANO-TECHNOLOGY PROCESSING MACHINES

Key features in nanofibering process are highly engineered fibers with diameters less than 500 nm (1 nm = 10^{-9} m). In comparison meltblown or spunbond micro fibers range in the area of 0.9 to several micrometers and e.g. merino wool fibers range around 12-24 micrometers. A human hair has a diameter around 80 micrometers and is about 200 times bigger in diameter than an average nanofiber. [2]

Company assigning this work is the first company in the world providing commercially available industrial scale equipment for the production of nanofibers. Their proprietary Nanospider electrospinning process allows the customers to make nanofibers with distinct fiber diameters from 80 nm to 500 nm or higher with a standard deviation of fiber diameter of 30% or less. The fiber diameter always relates to particular spinning conditions and chosen material. The properties of non-wowen from nanofibers are low density, large specific surface area, small pore size equals to good breathability, high porosity, excellent mechanical properties in proportion to weight, posibility to incorporate different additives and it has high pore volume. Most common usage of these materials is in the field of studies where the nanofirebers can be essential improvement. High potential for use of this technology is in: [1]

- Air filtration
- Liquid filtration
- Performance apparel
- Acoustic applications
- Medicine
- Battery separators
- Inorganic materials

Due to its dimensions and thus to its unique features, nano-materials show an incremental improvement of final products (for example in comparison to micro-materials). Therefore it is essential for further grow these technologies and scaling up to the mass production and low cost the high volume production. Help to the newly developed wire nanotechnology process which provides wider area of the machine usable for nanofibering the analysis of the functional subassemblies are essential for the improvement. The products must be designed for:

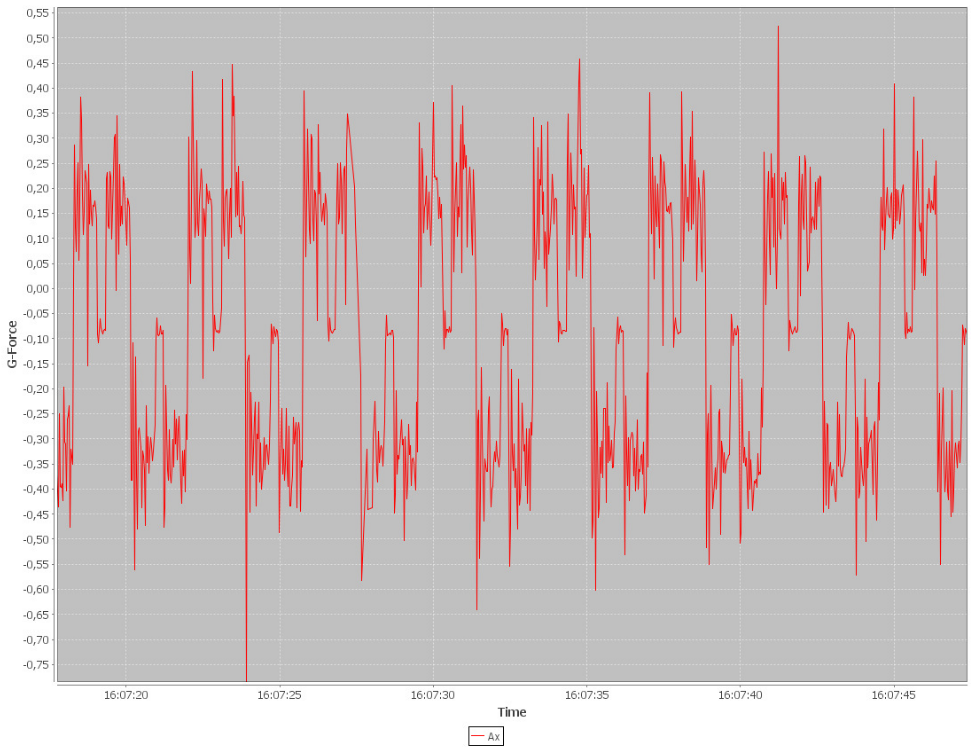
- Ease of use
- Flexibility
- Modularity from few subassemblies
- Scalability
- Stiffness of the assembly
- Component separability from high voltage

Nano-fibres have a great potential in many applications and industrial production is the key to their use in environmental protection. The considerable porosity and high surface and volume coefficients of nano-fibres offer extraordinary options for use in membrane technologies. Molecules, macromolecules and cells may be connected by nano-fibres and such modified nano-fibres may be subsequently used in many areas from waste processing to chemical analyzing and diagnostics through the use of biosensors. Furthermore, nano-fibres may be used in producing energy from renewable resources. Nano-fibres can replace both classical silica cells and the new generation of cells with nano-composites. They also enable operation in aggravated light conditions (no sunshine) and the use of mobile power sources (the combination of solar cells with batteries for nano-fibres). [3]

Functional subassembly as is also linear guidance system, carriage and nanotechnology head being analyzed in this work need to be optimized for the nanofibering process which is very complicated and each subassembly has truly important part to the quality of the process and influence on the amount of fibers being produced. Electromagnetic fields from the wires, organic and non-organic materials, materials of the wire and other topics honestly connected to the quality of the process are not described in this work and therefore the task was to analyze only the construction and design of the linear guidance system for the biggest nanotechnology machine being developed in the company. High voltage lead has to be considered and taken into account that all electrically conductive parts has to be separated by the rate at least 5mm/kV.

2.1. Carriage with head acceleration measurements

In the current design is the center of gravity (COG) way out of the connection belt axis (see chap. 4.3.1.) and therefore there is an surmise that during movement of the whole mechanical assembly the wrong mass alignment brings higher reaction forces from the energy chain and moments to all of the parts as well as to the linear guidance than if the tooth belt connection would be as close as possible to the COG of the whole system. These irregularities evince as non-straight move of the head shown with jerky movements, vibrations to the PP and aluminum frame and unstable acceleration measurement.



Picture 1: Irregular movement of the assembly acceleration measurement

From this reason the task is to find the optimized carriage placement compare to the current design and reduce the weight of the whole system as much as possible as well as to compare optimized design to the one used in current machines resulting to better acceleration moment of the functional subassembly. Peaks of the acceleration by measuring with the MEMS chip reached acceleration 4 – 5 m.s^{-2}, which refers to set up velocity profile of the servomotor controlling that the carriage has to transfer the 1600mm in 1,6sec. However this value supposes to be overreached in the future.

2.2. Material properties used in the linear guidance system

Materials used in the construction of this assembly must be strongly acid resistant, current non-conductive, sufficiently sturdy (tensile strength above 400MPa) and stiff connections for dynamic movement. Therefore previous experience in nanotechnology machine design as well as industrial material availability and cost of these materials selected the best fitting options described further in this chapter due to their excellent suitable properties.

2.2.1. Dural 424210 aluminum alloy material properties

High strength, low weight alloy which is in the solution heat-treated and aged condition, mechanical properties are as good as, or better than, low-carbon steel. There is limited weld ability and it has poor corrosion resistance, but reliable chemical resistance for use in nanotechnologies.

The main alloying constituents are copper, manganese, and magnesium. A commonly used modern type of alloy type is this 424210, which contains 4.4% copper, 1.5% magnesium, 0.6% manganese and 93.5% aluminum by weight. Typical yield strength is 450MPa, with variations depending on the composition and temper. [4]

Table 1: Aluminum alloy material properties [5]

Electrical Properties	
Electrical resistivity (μOhm cm)	5.0
Temperature coefficient (K^{-1})	0.0022-0.0026
Mechanical Properties	
Elongation at break (%)	<22
Hardness - Brinell	115-135
Izod impact strength ($J\ m^{-1}$)	8,0 - 22,0
Modulus of elasticity (GPa)	73
Tensile strength (MPa)	420-500
Physical Properties	
Density ($g\ cm^{-3}$)	2,8
Thermal Properties	
Coefficient of thermal expansion @20-100C ($x10^{-6}\ K^{-1}$)	22,5
Thermal conductivity @23C ($W\ m^{-1}\ K^{-1}$)	147

2.2.2. Polypropylene (PP) material properties

Excellent resistance to stress and high resistant to cracking (i.e. it has high tensile and compressive strength). It has high operational temperatures with a melting point of 160°C. Excellent dielectric properties and it is highly resistant to most alkalis and acid, organic solvents, degreasing agents and electrolytic attack. On the contrary is less resistance to aromatic, aliphatic and chlorinated solvents and UV. Because it is non-toxic, non-staining and easy to produce it is an appropriate material for weld assemblies from boards and due to its price is also available economic material for nanotechnology applications with high demand upon chemical and dielectric resistance. [6]

Table 2: Polypropylene physical properties [7]

Physical Properties:	Value:
Tensile Strength:	0.95 - 1.30 N/mm^2
Notched Impact Strength:	3.0 - 30.0 Kj/m^2
Thermal Coefficient of Expansion:	100 - 150 x 10^{-6}
Max. Continued Use Temperature:	80 ^oC (176 ^oF)
Melting Point:	160 ^oC (320 ^oF)
Glass Transition Temp. (atactic):	-20 ^oC (-4 ^oF)
Glass Transition Temp. (isotactic):	100 ^oC (212 ^oF)
Density:	0.905 g/cm^3

2.2.3. Stainless steel material properties

Stainless steel is a type of alloy steel that resists rust and other forms of corrosion and has an attractive appearance. Stainless steel contains chromium which provides the unique stainless and corrosion resisting properties. Stainless steel has a unique self-healing property. Due to the alloying elements used, a thin, transparent layer is formed on the surface. In case the surface is scratched or damaged otherwise, this thin layer, which is only a few atoms thick, immediately rebuilds with the assistance of oxygen from air or water. This is the reason why stainless steel does not require any coating or other corrosion protection to remain bright and shiny even after decades of use. [8]

Stainless steel products have many significant advantages over other metals:

- Resists corrosion leading to long-life durable parts
- Retains strength even at high temperatures and resistant temperatures shock

- Hygienic due to the smooth and minimally porous surface
- Bright aesthetic appearance
- Easily machined, welded, formed and fabricated
- Usually non-magnetic - therefore useful for nanotechnology applications
- Excellent fatigue and impact resistance

Table 3: Stainless steel physical properties [9]

Physical Properties	Metric	English	Comments
Density	8 g/cc	0.289 lb/in³	
Mechanical Properties			
Hardness, Brinell	123	123	Converted from Rockwell B hardness.
Hardness, Knoop	138	138	Converted from Rockwell B hardness.
Hardness, Rockwell B	70	70	
Hardness, Vickers	129	129	Converted from Rockwell B hardness.
Tensile Strength, Ultimate	505 MPa	73200 psi	
Tensile Strength, Yield	215 MPa	31200 psi	at 0.2% offset
Elongation at Break	70 %	70 %	in 50 mm
Modulus of Elasticity	193 - 200 GPa	28000 - 29000 ksi	
Poisson's Ratio	0.29	0.29	
Charpy Impact	325 J	240 ft-lb	
Shear Modulus	86 GPa	12500 ksi	
Electrical Properties			
Electrical Resistivity	7.2e-005 ohm-cm	7.2e-005 ohm-cm	at 20°C (68°F); 1.16E-04 at 650°C (1200°F)
Magnetic Permeability	1.008	1.008	at RT
Thermal Properties			
CTE, linear 20°C	17.3 µm/m-°C	9.61 µin/in-°F	from from 0-100°C
CTE, linear 250°C	17.8 µm/m-°C	9.89 µin/in-°F	at 0-315°C (32-600°F)
Specific Heat Capacity	0.5 J/g-°C	0.12 BTU/lb-°F	from 0-100°C (32-212°F)
Thermal Conductivity	16.2 W/m-K	112 BTU-in/hr-ft²-°F	at 0-100°C, 21.5 W/m°C at 500°C
Melting Point	1400 - 1455 °C	2550 - 2650 °F	
Solidus	1400 °C	2550 °F	
Liquidus	1455 °C	2650 °F	

3 SEARCH OF LINEAR GUIDANCE SYSTEMS (LGS)

Wire electrostatic nanotechnology is a patented in the company with cooperation with Technical University of Liberec and it is needle-free high voltage and free liquid surface on wire process. The technology is based upon the discovery, that it is possible to create Taylor Cones and the subsequent flow of material not only from the tip of a capillary, but also from a thin film of a polymer solution electrospinning on thin wire.

The technology must enable the company to build industrial scale production equipment without nozzles, needles or spinnerets. The technology allows the production of nanofibers from polymers solved in water, acids or bipolar solvents as well as from melted polymers and is suitable for the production of organic and inorganic fibers. This versatile technology is easily adapted to a variety of process parameters for the optimization of the specific properties of the produced nanofibers. [10]

Revolutionary nanotechnology and importantly the linear guidance system has to fulfill the following requirements in order to maximize the customer demand:

Simplicity

Wire nanotechnology uses simply wire electrodes of particular material assignment, being submerged in a polymer solution by the nanotechnological head with four retarders at the top of the head. It is mechanically simple and has no parts easily clogged (in comparison to needle-type electrospinning). As well as the linear guidance system as one of the most important subassemblies of the machine has to fulfill requirements of simplicity as much as possible.

Productivity & Quality

The numbers of fibers per machine width is given by the distance of the Taylor cones. Natural physics defines this distance and therefore linear guidance system and the space for nanofibering needs to be adjustable for researching of new materials in the same machine, rather than using individual needles in older technologies. This allows higher fiber packing density and thus an increased productivity as well as better fiber homogeneity and more consistent web morphology. Stiffness of the linear guidance system is therefore essential for the productivity and quality as well as sustainability of the process in long term life precondition.

Flexibility

Wire nanotechnology is flexible to allow the production of a nanofiber layer which meets exactly the final product needs. It is possible to optimize the critical parameters of the equipment for the selection of the customer. Important to know is the result nanofibers that the customer needs to achieve which is concluded especially from the guidance system length and depending wire length for each machine, choice of the material being processed as well as the retarders for nanotechnology selection important for the thickness of the layer being electro-processed, where the current intensity can be set by the amplifier and is not depending on the guidance system.

Individuality

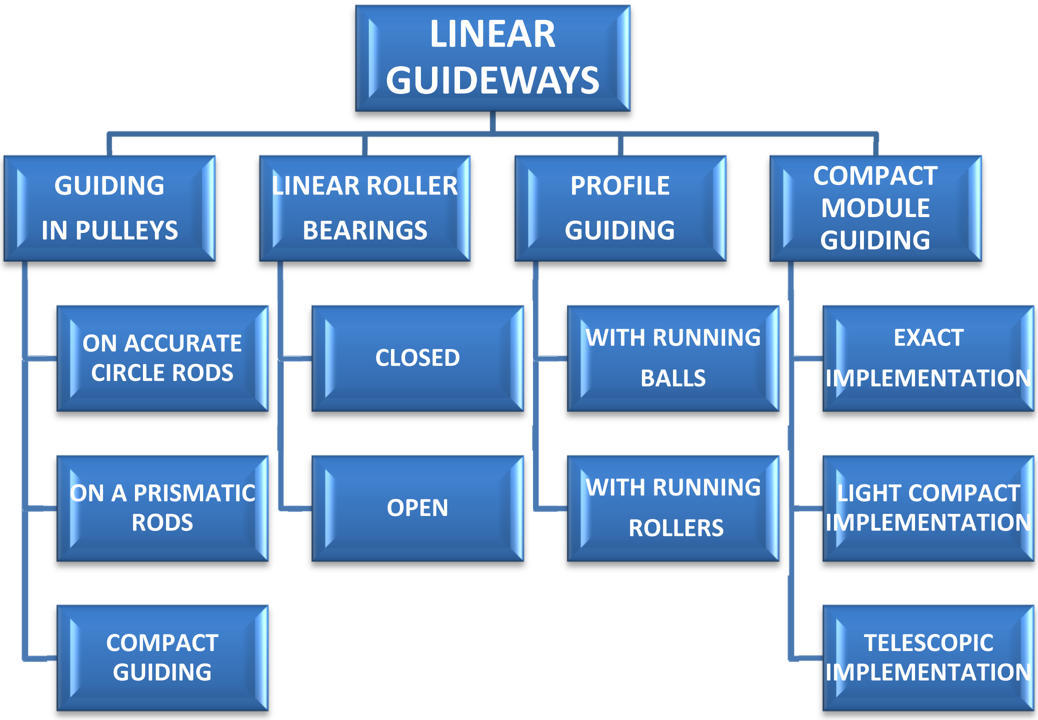
The technology allows optimizing the results in nanofiber production through precise adjustment of many process parameters, which are decisive for final product:

- Solution parameters (conductivity, temperature, surface tension, etc.)
- Environmental parameters (temperature, humidity etc.)
- Base material parameters (cross and surface electrical resistance, etc.)
- Equipment parameters (voltage, electrode distance, etc.)

Linear guidance system must allow in the machine:

- High productivity and scalability of the nanofiber production
- High fiber diameter and web uniformity due the consistent carriage movement
- Economical operation and easy maintenance
- Flexibility in used polymers and substrates as well as their distribution

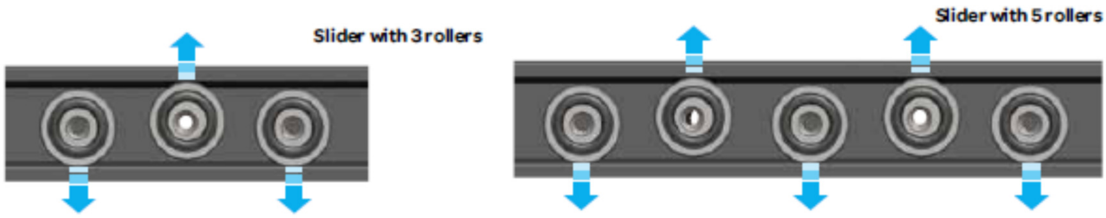
Mentioned requirements above gives the direction what kind of linear guides can be used and what requires the application. In the working space of this machine is the most important acid resistance and small particles sealing. While fibering several filaments usually get allowed and are freely moving in the environment. Therefore during the carriage and head moving process these filaments can get easily caught in the guidance system and influence the work ability as well as functionality, durability and the lifetime of the friction bearings in case of guiding in pulleys. From this reason is demanded choice of enclosed guide ways (see Pic. 2) or at least have proper covering of the guiding system against the free filaments and other impurities including drops of fluidic polymer containing the strong acids. These drops are most of the time caught in the bath of the nanotechnology head, but in case of change of the head design this has to be taken into account. Current design with guiding on circle rods with plastic friction bearings has to be often cleaned up and the bearings often replaced.



Picture 2: Overview about roller guidance systems

In the picture 2 above can be seen that the basic deviation in the types of guidance system is split up by the type and shape of the guiding rods and then by the elements being rolled on them by the force movement actuator.

Search of applicable linear guidance system was made and boundary condition where taken into account assigned by the specification of the company from the previous usage experience. The most important requirement was the possible length of the system suitable into the current corpus of the machine (>1600mm) for eventual enlarging of the machine working space and type traction force with its drive for the carriage ($<5 m.s^{-2}$). The whole enclosed embodiment has to be resistant to acids and separate the high voltage, which is narrowing the selection for the used materials of the construction. Dynamically moving assembly is attached to the energy chain as well as is his own weight which is restricting the selection for maximal lateral loading and adjustability accuracy with repeatability of the retrogressive movement.



Picture 3: Roller loading position [11]

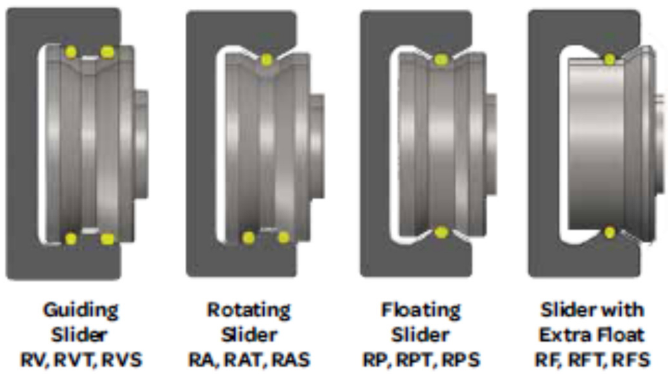
Several linear guidance systems were searched and as highly appropriate were chosen the roller system which is easily adjustable and easy to incorporate into to the current machine design. This design of pulleys (see Pic. 3, 6) nicely eliminates the mistakes in parallelism observed in current design causing trouble movements (Tab.4).

Table 4: Spona-Rol TwinRace guiding system [11]

Supplier and type of LGS	SPONA-ROL s.r.o. TWINRACE
Maximal crossing velocity	8 [m / s]
Maximal length of the system	4000 [mm]
Accuracy and repeatability of the movement	Elimination of the mistakes in parallelism is thanks to one floating and one stable roller pulley.
Bearing capacity and max. loading	Axially: 27000 [N], Radially 10800 [N]
Type of drive and transmission	Tooth belt with servomotor or alternatively on the carriage with different drive system
Roller elements and bearings	Suitability of 5 pulleys with two rows roller bearing, where the body of the carriage would be galvanicly improved.
Guidance materials	Cold rolled steel with superfinished guidance surfaces with low temperature nitridation.
Lifetime, lubricant need and resistance against chemicals and acids	Pulleys with whole life fat filling and itself greasing. Compact carriage and ease of assembling
Suitability to high voltages and temperatures	-30°C až +80 °C High voltage suitability is not stated in the catalog.

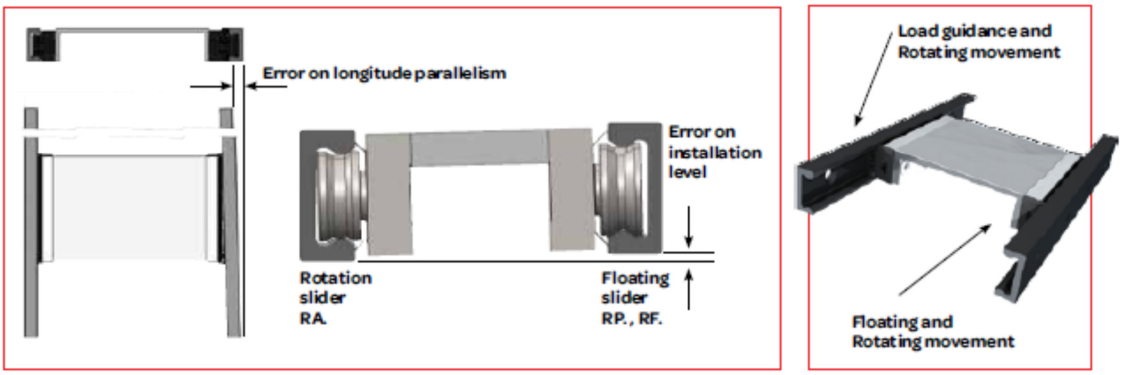
Picture 4: Roller contact points [11]

Each design of different pulley expresses its function into the great ability to eliminate producing mistakes often observed after the construction of the bolted aluminum profile frame of the whole machine (see Pic.4, 5 and 6). Testing of this kind of guiding system will bring easier and cheaper solution into the complete machine design with minimum design changes in the working space (see Pic. 6). There needs to be researched the option whether the manufacturer would be able to produce the guidance rods from stainless steel for better application in this chemically aggressive environment to protect the parts against corrosion and assure the long life (see Tab.4).



Picture 5: Slider contact points [11]

Different supplier state changeable information about their linear guiding systems and use of these systems would have to be further discussed with the manufacturer or eventually slightly changed for possibility of use in the Nanotechnology line. The chemical resistance and appropriateness for this application has to be tested prior using in the final design of the machine. Selection of two suitable different concepts is shown in the table 4 and 5, where can be compared their properties as well as materials used. More information about other linear guiding systems can be found in the appendix with the whole search included.



Picture 6: Self-aligning roller guidance system combination [11]

Other possibilities exist according to the picture 2 above and the search is included in the appendix with all considerations mentioned in chapter 3 needed to consider while researching the new linear guidance system. For comparison with the Spona-roll TwinRace guiding system is shown the Güdel Monoroll system (mentioned in Tab. 5), which is able to achieve much higher velocities in the carriage movement but has lower loading acceptance. However it would be sufficient for this application and furthermore has to be researched the oil grease influence for the nanofibering.

Table 5: Güdel Monoroll linear guiding system [12]

Supplier and type of LGS	Güdel Monoroll (type F or L)
Maximal crossing velocity	20 [m / s]
Maximal length of the system	6000 [mm]
Accuracy and repeatability of the movement	± 1.5mm
Bearing capacity and max. loading	Axially: 2000 [N], Radially 1000 [N]
Type of drive and transmission	Servomotor with specific flange and specific transmission or eventual different drive system
Roller elements and bearings	Eccentric pulleys together with grain laths attached to the aluminum profile.
Guidance materials	Fully aluminum profile.
Lifetime, lubricant need and resistance against chemicals and acids	Pulleys with oil greasing and special wiping and possibility of filling up the lubricant. Compact carriage and ease of assembling.
Suitability to high voltages and temperatures	High voltage and temperature suitability is not stated in the catalog.

4 LOAD SET ASSIGNMENT FOR FEM ANALYSIS IN CREO – PRO/MECHANICA CAD SOFTWARE

Load assessment for the carriage is based on physical and material properties along with real machine usage condition. Usage setting is gathered in the table 6 below. Mass properties and data taken from the 3D CAD model with assigned proper material were compared with double control of exact material assignment of each component in the 3D CAD model (see Tab.6). The head assembly uses while running time independent mass flow of the polymer fluid in the pipe lead and therefore the total mass was considered as the highest 12kg with assumption that the pipes will be completely full with polymeric fluid even though it is known that eventual design 222 and 333 is lighter. From this reason the highest load on the carriage is caused with the highest mass in fact 12kg considered for the FEM calculations and reaction forces for all of the designs, which was measured at the oldest design 111. Consequently the question is to calculate and assign all forces to the carriage in order to get results from FEM analysis as close as possible to reality when this assembly supposes to accelerate maximally 5-10 m/s2 and the mass of the design will be maximum 12kg. All other conditions will truly show stress and displacement results lower than maximum load considered and therefore only the highest limits were taken for FEM static calculations for approval.

In this work three different design tasks has to be accomplished at the first place (see Tab.6). These tasks are consisting three different carriage designs and two different head designs in combination with assumption of fully supplied hoses with polymeric fluid, which is happening especially at the start of the process of nanofibering. More specifically start of the carriage movement. From this reason the FEM task is to revaluate the dynamic task to the static assignment which will substitute the moment in the movement with the highest load as well as assure the credibility of all of the design combinations possible to use the current machine.

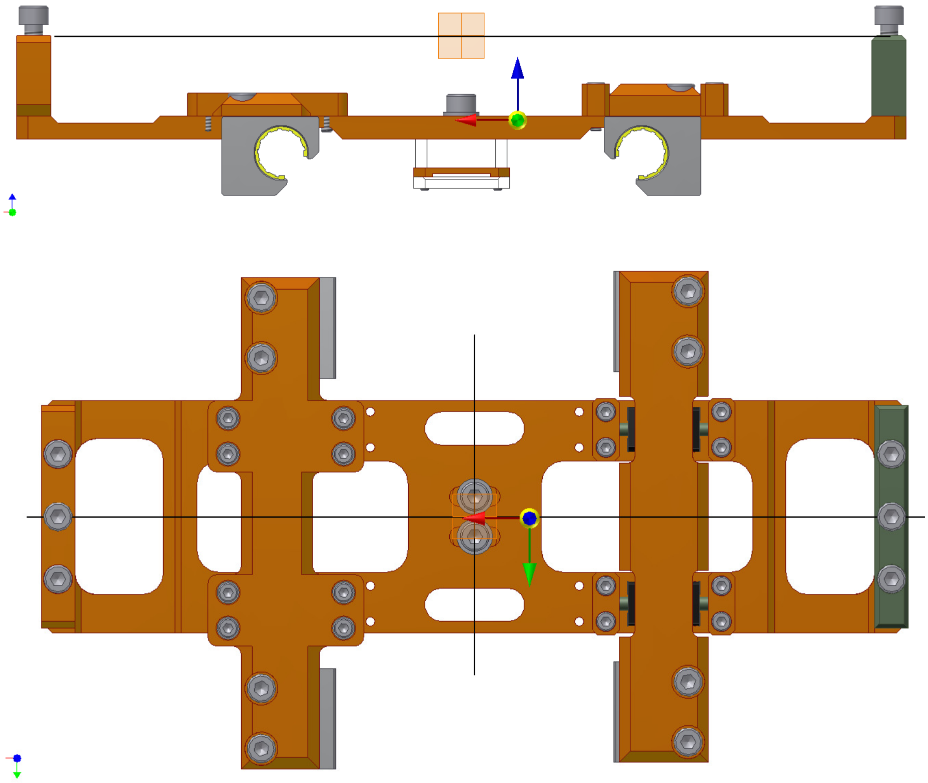
Table 6: Carriage design used assignments

Assembly	Carriage	Head	Total mass:	
1. **Mechanical assembly 111**	oldest bolt mounted	old	12	kg
2. **Mechanical assembly 222**	new design full volume	new	10	kg
3. **Mechanical assembly 333**	new light weighted design	**new**	**9,5**	**kg**

The goal of these calculations is to compare the maximum stress and displacement of these aggregates in order to design a new type of carriage with use of the new designed head in order to optimize them for the lowest weights in the same maximum load based on the knowledge obtained from these analyses.

Carriage 111 without head and top part of the carriage properties

Total mass [kg]	Displacement compare to center of the head		
	X [mm] -red	Y [mm] - green	Z [mm] - blue
2,62	**-24,7**	**0,82**	**-36,8**



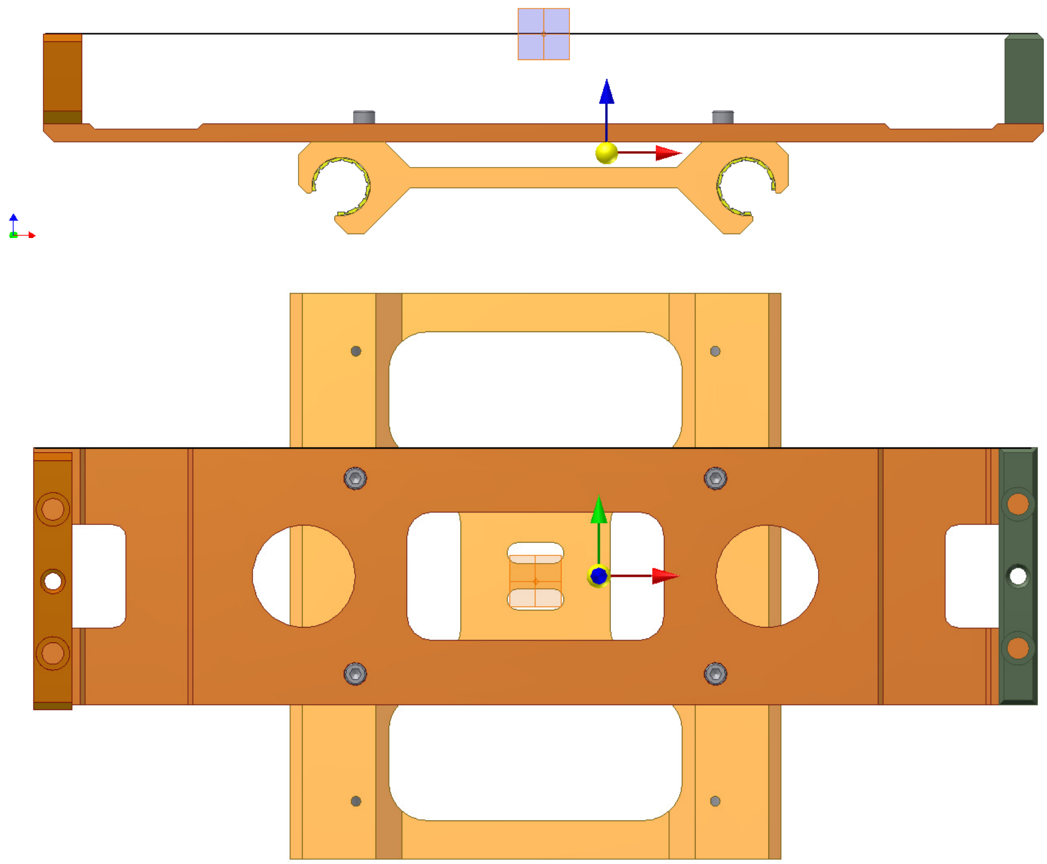
Picture 7: The oldest bolted carriage 111

Consequently the new design based on these calculations will assure that it will be feasible with the same maximum load and lower weight proceeding better smooth working process without jerky vibrations and linear guidance system overloading. This phenomenon will be proved and researched also with the FEM modal analysis at the optimized design, which will show the feasibility of the design as well as explain closely the phenomenon happening in the machine. Shapes of the eigenfrequencies explain the assembly vibration behaviour while moving along the travelling distance.

Lower weight in the moving assembly will cause lower vibrations and load on the linear guide and aluminum frame of the whole machine over all. Aluminum profile frame of the machine might during the time of machine working life change slightly as well as after the transport of the nanotechnology line to the costumer.

Carriage 333 without head and top part of the carriage properties

Total mass [kg]	Displacement compare to center of the head		
	X [mm] -red	Y [mm] - green	Z [mm] - blue
2,44	24,7	2,1	-46,5



Picture 8: The newest one piece carriage 333

Consequently mechanical properties of the carriage 111 and the carriage 333 were traced in tables above. Comparison of the total mass is showing that the design of a new carriage 333 expresses only the mass saving 2,62 – 2,44 = 0,18kg and move slightly the COG of the carriage in z direction closer to the belt center, but it is not critical and it does not have effect on better slide ability. Advantage in assembly 333 is that it is consisting from fewer parts and lower screw connections allowing eventual part loose ability. Dispersing of the load on one piece part is significantly better than on the previous assembly and it saves assembling time of the carriage with nanotechnology head.

4.1. Energy chain forces calculations

Prerequisites for these calculations are from the parts used in the current machine and some minor assumptions had to be made for simplification and achieving the value close to the reality in order to get as close as possible with FEM calculations to the actual load and add there such boundary conditions. These forces are almost impossible to physically measure and therefore following calculations were proceeded. Prediction prior the FEM calculations says that even the low energy chain forces has huge impact in the carriage movement since it is mass moving relatively fast which is led out of the COG of the assembly along with the fact that the energy chain is attached at the heavier half and simply is it not a part without friction and it has to add extra load on the functional assembly. Displacement of the head has furthermore impact on the quality of wire nanofibering or eventual wire crack.

Moving assembly of the energy chain contains parts:

- 2x Energy chain IGUS E2 mini B15i.015.075.0, Lk (length) = 1647mm + end connections type 1015.12P.
- The first energy chain carries: 4x electro-cables for the sensors with the diameter 2mm
- The second chain carries: 2x 8mm Teflon hose with 1mm wall, which is hidden in protection hose of diameter 10mm

Mass properties of the Energy chain:

M_1en_CHain = 0,35kg/m * length 1,647m = app 0,58kg (1)

Total Energy chain weight = 0,58kg * 2 = 1,16kg (2)

Table 7: Total energy chain weight calculations

Length app. 1700mm x	Amount	Estimation	Data mass (kg/m)	Total mass (kg)	
Sensor Electro-cable	4x	10kg/km	0,01	0,068	
Teflon hose diam. 8mm	2x	80g/m	0,08	0,272	
Protection hose daim. 10mm	2x	90g/m	0,09	0,306	
Mass sumation:	8		Total hoses-cable weight:	0,646	**kg**
				+	
			Energy chain weight:	1,16	**kg**
				=	
			Total energy chain weight:	**1,806**	**kg**

Cable masses were approximated and estimated to the most common values of cable suppliers where the deviation and differences are low in comparison with data used.

F_en_ch_horizontal = m * a = 1,806 kg * 5m/s2 = 9,03 N (3)

Due to the fact that the energy chain is working in the horizontal application (3) and it is supported in two connections the total weight is dispersed in the worst scenario for half vertically. Therefore the vertical load (4) from the energy chain will be calculated from the half of the weight and is equal to:

F_en_ch_vertical = 0,5 * m * a = 0,5 * 1,806 kg * 5m/s2 = 4,5 N (4)

In reality these forces (5), (6) is difficult to measure since many factors can influence its value and some reactions are captured in the joints of the energy chain and in the stiffness of mechanically mounted assembly and in the energy chain. From these reasons these forces were taken for the FEM calculations as the worst case and increased by the safety factor = 1,1 for rounding up the value.

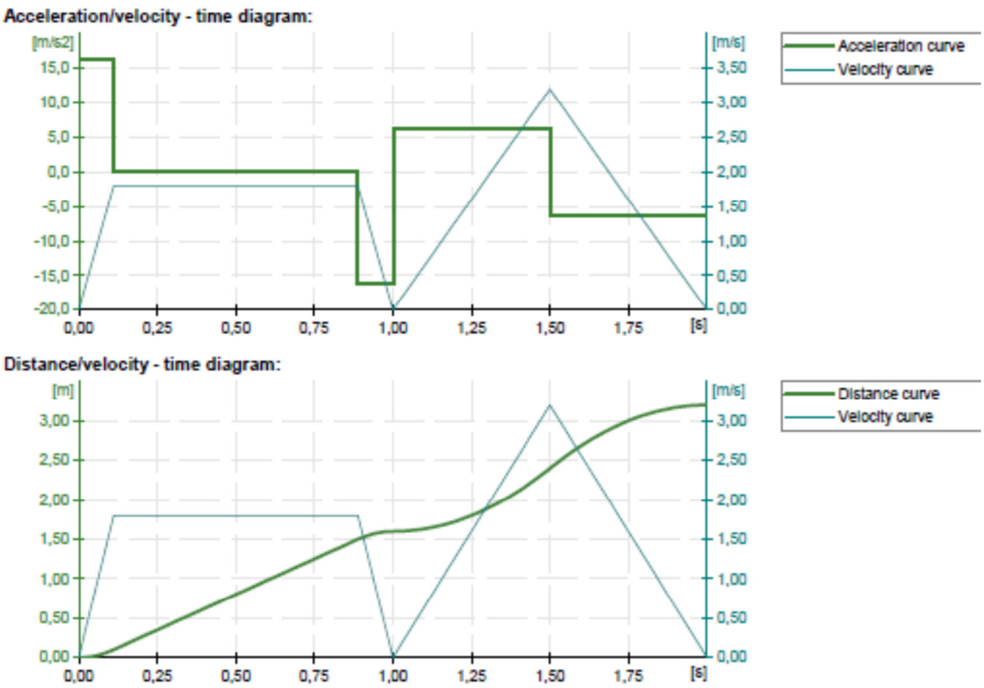
F_en_ch_horizontal = 1,1 * 9,03 N = 10 N (5)

F_en_ch_vertical = 1,1 * 4,5 N = 5 N (6)

Suggestions how it would be possible to measure these forces is to try connect some longitudinal measurement between the energy chain and the carriage in the machine and then only jerk the carriage without further movement. In this work was attempt for it, but unsuccessful measurement so therefore it was followed up only with the calculations considered satisfactory.

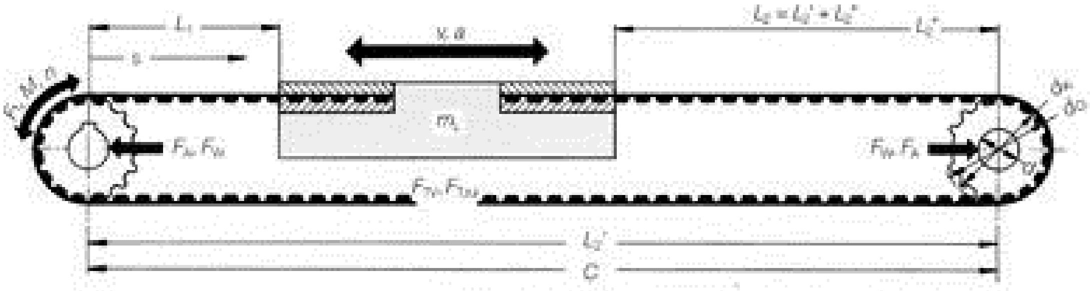
4.2. Linear drive kinematic calculations

First of all for the linear drive calculations has to be made some preliminary assumptions concluding at first place the shape of velocity profile needed to achieve for smooth and sufficient movement across the working distance achieving the movement in some certain time of traveling with the weight carried. In case of assumption for this work the working distance for carriage movement is 1600mm and initial time for return of the carriage is around 3 - 4sec with the mass being 12kg. However the intention is to increase the speed as well as reduce the time of traveling in the future design resulting into faster electrospinning in the working space causing higher nanofiber production of the machine. In order to prescribe correctly the movement velocity profile (see Pic.9) has to be programmed in the controlling system. This possible profile of movement (Pic. 9) is considered as future target design improvement. Furthermore has to be also taken into account that there is idle time approximately 0,3sec in reversible movement.



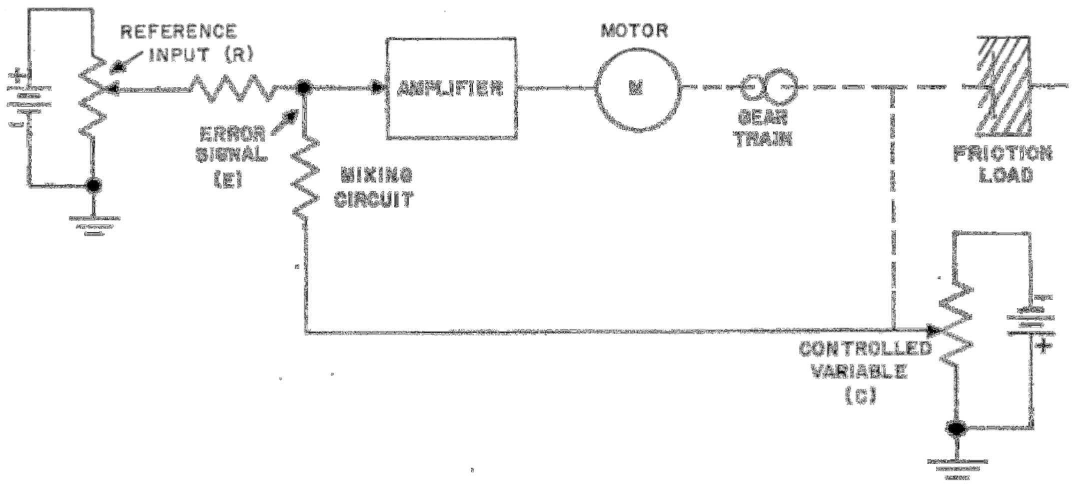
Picture 9: Servomotor velocity profile prescription [13]

Commonly used and the easiest profiles are either "A" profile or trapezoidal profile (see Pic.9). Both of these profiles is possible to set in the setup of the machine along with the shape of the profile made by assigning the accelerating distance, constant movement and decelerating distance. Both can be seen in the example case on the picture 9, where from 0 to 1sec is the shape of trapezoidal profile and from 1 to 2sec is the A profile most commonly used.



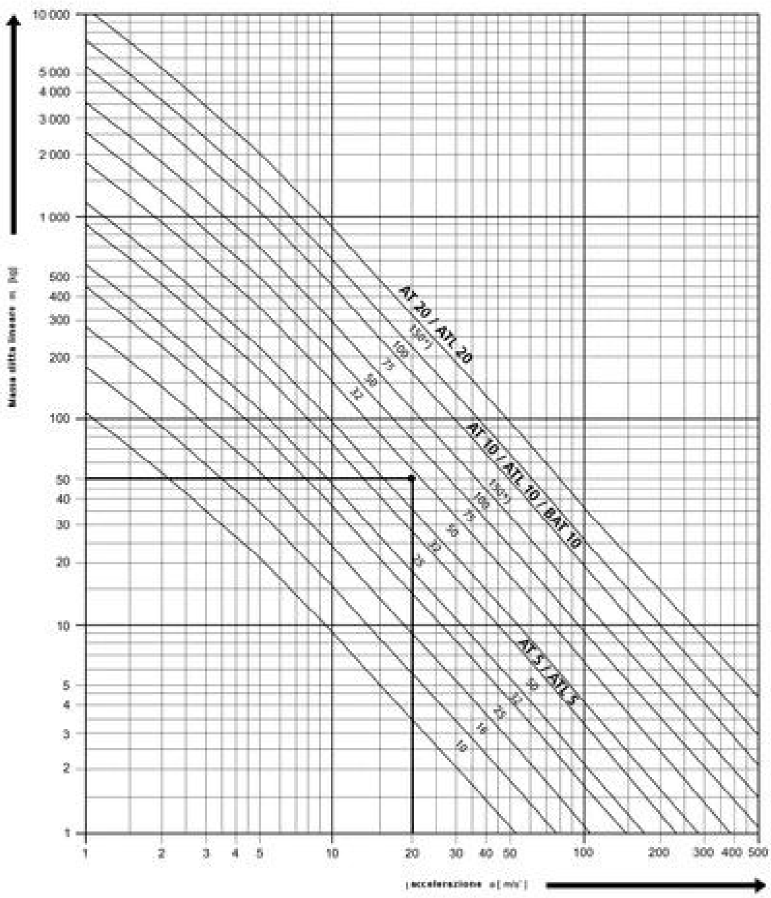
Picture 10: Linear drive scheme [14]

Surrounding structure of the linear drive has to assure that all assembly modules will be not overloaded and will meet the minimal requirement for that particular part as well as it will be dimensionally stable assuring the repeatable continuous movement accuracy of the system (see Pic.11). The ease of this system permits by the motor transfer the rotational translation from the pulleys into the linear translation of the carriage with the nanotechnological head (see Pic.10).



Picture 11: Position follow-up Servomechanism [15]

The distance of travel per pulley revolution is defined with the selection of the pitch and the number of teeth of the drive pulley. The belts transmit reliably and fast the rotational movement of the pulley trough transmission into the linear motion. From this reason any safety factor will be included because reliability of the belt considerer nearly 100%. With extreme loading of the belt in a short time is recommended the pretension of the belts which supposedly reduce the amount of tension also in the pulleys and the whole assembly over all. These aspects are controlled by position follow-up servomechanism which is being programmed in the special software environment according to the manufacturer of the software (see Pic.11). No other elongation of the belt or other parts is expected and it may occur only in case when the belt would be used over the working temperature limit, which is not expected in this nanotechnology usage in ambient temperature environment.



Picture 12: Coarse choice of the timing belt design [16]

It is possible tentatively choose the type of the belt according to the charts of the suppliers (f. e. Pic.11). Due to the known mass (=12kg) for linear slide and the maximal acceleration (a=10m/s^2) being prescribed the belt can be found. For complete mass assumption has to be included also the weight of the driven pulley and weight of the timing belt. Weight of the timing belt can be found in technical data sheet provided by the supplier as well as the density of pulley construction material must be taken into account. Standard is saying that the pulleys have to have 25 or more teeth otherwise wider belt should be selected.

For this machine is recommended to control especially accuracy of the system diminishing the deviations in procedure of nanofibering and the pre-tension limits the errors in the movement for achieving consistent repeatability around +/-0,1mm per traveled meter. Other important characteristic of the linear system is the capability to convert the turning angle of the pulley into the set carriage movement profile via the belt. The achievable positioning precision depends indeed on the loading and friction forces while processing. Furthermore the inverse fault can occur by the effect the dirt and increase of friction being gathered over the travelled distance especially in the place of reverse movement as well as the long length and pitch deviation will count up.

Furthermore equations following bellow can be used to comprehensively compute the linear drive for the belt system being used in the current machine as well as eventually used as future linear drive system. The circumferential force F_u has to be calculated according to mass and required acceleration, where consequently moving mass is a decisive factor for drive selection.

Thus circumferential force at the drive pulley F_u equals to:

F_u = Acceleration force + lifting force + friction force + reactions =

= m*a + m*g + m*g*f + F_en_ch_horizontal [N], where (7)

Acceleration force is necessary to accelerate the linear drive with mass of the carriage and the nanotechnological head. The lifting force is necessary for movement acceleration due to gravity in vertical applications. Therefore for this case will be neglected and equal to 0N. A friction force is opposite to the moving direction in the amount of friction bearings in case of linear roller guidance as well as in this case horizontal force from the energy chain as (5).

Thus for the worst case (7): F_u = 12*10 + 12*9,81*0,1 + 10 = 142N

For currently used case (7): F_u = 12*5 + 12*9,81*0,1 + 10 = 82N

Maximal torque needed to apply by the motor on the d_0 driven pulley is then,

$$M\_max = \frac{d_0 * F_u}{2 * 10^3} = \frac{55 * 142}{2 * 10^3} = 3{,}9\ [\ Nm\ ]$$

And maximal torque needed to apply by the motor on the driven pulley in the current design assuming the highest acceleration of $5m*s^{-2}$ is then,

$$M\_currently = \frac{d_0 * F_u}{2 * 10^3} = \frac{55 * 82}{2 * 10^3} = 2{,}3\ [\ Nm\ ]$$

Output revolution at the transmission is:

$v\_max = \omega * d_0 / 2$ ➔ $\omega = 2 * v\_max / d_0$ [$rad*sec^{-1}$], where v_max is maximal velocity of the carriage. Therefore the rotational speed after the transmission is:

$n = (60*v\_max) / (\pi * d_0)$ [$rev*min^{-1}$], when v_max is calculated as (8)

$$v_{max} = \frac{d_0 * n}{19{,}1 * 10^3} = \sqrt{\frac{2 * s_b * a}{1000}} \quad [\ \mathrm{m} * \mathrm{s}^{-1}\ ]$$

, where s_b is the acceleration or deceleration distance substituted according to the velocity profile being calculated (see Pic.9).

Traveling time can be calculated then according to basic formula t = s / v [sec], where s is particular traveling distance in the profile and v is velocity calculated for that distance as well. The whole linear drive system suppose for the smooth and correct work ability be pre-tensioned, when under maximum effective circumferential force F_u from acceleration as well as from braking case the slack span side of the belt stays tight. Therefore the minimum pre-tension force $F_{pre\text{-}tension}$ is being considered:

$F_{pre\text{-}tension} = F_u$ [N] , where (9)

The highest span forces F_{span} will occur at the tight span side in move direction (10), when both pre-tension force $F_{pre\text{-}tension}$ (9) and circumferential force F_u (7) are acting together. Pre-tension force supposes to be static and the circumferential force has dynamic character. Other safety for the timing belt has to be considered the tensile force, which can be found in the technical data sheet and must be bigger according to the safety factor than occurring F_{span}.

$F_{span} = F_{pre\text{-}tension} + F_u$ [N] (10)

Further the pre-tension distance can be calculated, meaning that the tensioning station can be mounted at any position of the timing belt. Elasticity c_belt value of the timing belt must be again found in the technical data sheet. The linear system evinces a variable elasticity c in the working process. Attitude of the elasticity behavior of the linear slide therefore depends on the length of proportion L_1 and L_2 where the pre-tension station is being placed from each side. Consequently the elasticity will be minimal when L_1 and L_2 are equal.

$$c = \frac{Length}{L_1 + L_2} * c_{belt} \quad [\frac{N}{mm}]$$

4.3. Center of gravity (COG) optimization

Analogy for this optimization was to move the carriage including all accessories and change the design of the head connection in order to achieve the action center movement point in the axis of the belt connection right below the COG for the whole assembly. The design must be exactly high so therefore there will be any possibility to get the COG of the whole system exactly to the belt connection and it will be always above instead. In the current design was considered primarily the position of the linear guidance system to be as close as possible to the COG of the head, but was not taken into account the complete COG of the whole system. Therefore got fetched the phenomenon observed in the working machine with vibrations and jerky movements on the moving assembly. The displacement can be measured as 11mm off the center of the head as described in the chapter 4.3.1 bellow in the oldest first 111 design.

Therefore there is intention to reduce the difference from the center of the belt connection compare to the COG of the whole subassembly close to zero with consideration of the mass reduction by reducing amount of the parts and optimization of the new design for the lowest weight with the same load prescription instead only to the COG of the head. These optimizations require different way of observation and thinking from the designer of the machine where this linear guidance system is used and performs its important part in the excellent work ability. Previously was not taken into account the COG of the whole assembly but on the other way were adding extra weights to limit this value and get the COG of the head close to the center of the belt connection instead.

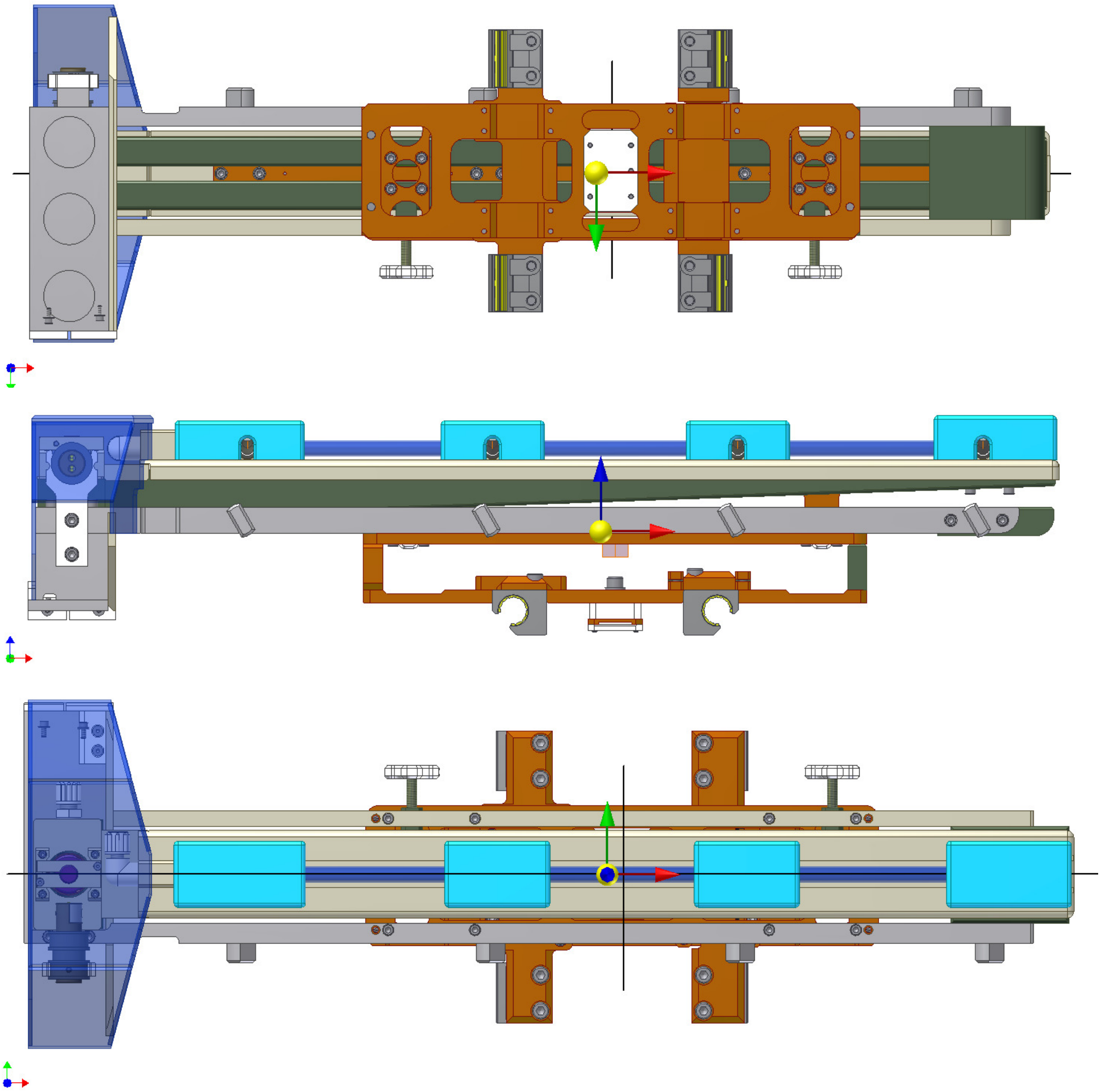
While designing this system previously was not taken this into account and showed important aspect in the design and controllability point of view afterwards with upcoming experience and troubleshooting. Change in the design will lead to the smoother movement diminishing the jerky movements blocking the assembly between the guidance systems and ruining quickly the friction bearings. Chapters pursuing these steps are from 4.3.1. to 4.3.5. where the optimization proceeded in the chapter 4.3.5. supposes to be the ideal final design with new 333 design of the carriage and usage of the new light weighted head. The design 222 was not included in the optimization from obvious reason that it can be further optimized at least into the potential design 333. In the optimization was not taken into account the mass of the polymer fluid filling up the hoses, because these data were observed from 3D CAD models with assigned proper materials used in reality. Tracked COG coordinate was the X direction which is essential value for getting the right position of the belt tractional force and place of attachment.

4.3.1. Present design of carriage 111 with new light weighted head

First of optimization designs is the oldest design of bolted carriage 111 (see Pic.13), which uses also older heavier head. But because the company experience from dispatched and working machines let the designers to reduce the weight of the head. The optimization with the light weighted head was only followed up. Light weighted head is considered as irreplaceable and therefore was worked with it and the mass reduction is followed up especially at the carriage and its parts.

This design has the center of gravity 11,2mm off in longitudinal direction from the COG of the head. However this value was reached by adding an extra counter weight at the end of the head and it explains nonsense of the extra weight and was leading to other optimization following steps in to remove the counter weight and optimize the complete COG of the whole subassembly.

Total mass [kg]	Displacement compare to center of the head		
	X [mm] -red	Y [mm] - green	Z [mm] - blue
8,15	-11,2	-0,4	9,4

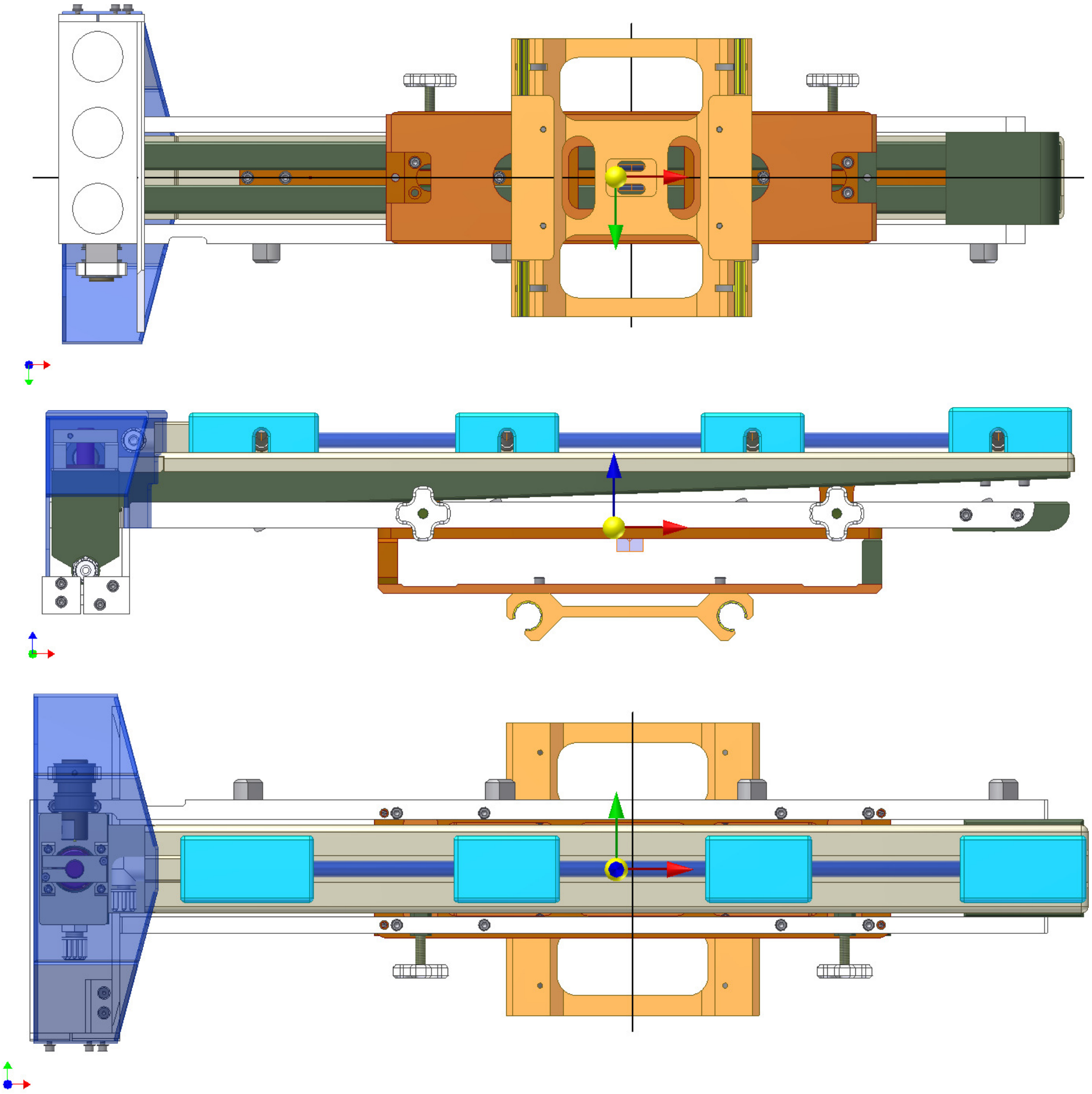


Picture 13: Design 111 optimization

4.3.2. Carriage 333 with new head current design with counter weight

New design of the carriage brought amount of parts reduction, slight mass reduction by 0,14kg, but the displacement of the center of gravity compare to the center of the head stayed nearly the same like in the design 111 (=11,2mm) where it reached value 12,3mm. Expectedly this design change improved only stiffness of the subassembly, reduced the amount of parts used and improved the assembling with time reduce, but did not solve the jerky movement issue.

Total mass [kg]	Displacement compare to center of the head		
	X [mm] -red	Y [mm] - green	Z [mm] - blue
8,01	**-12,3**	**-0,4**	**8,1**

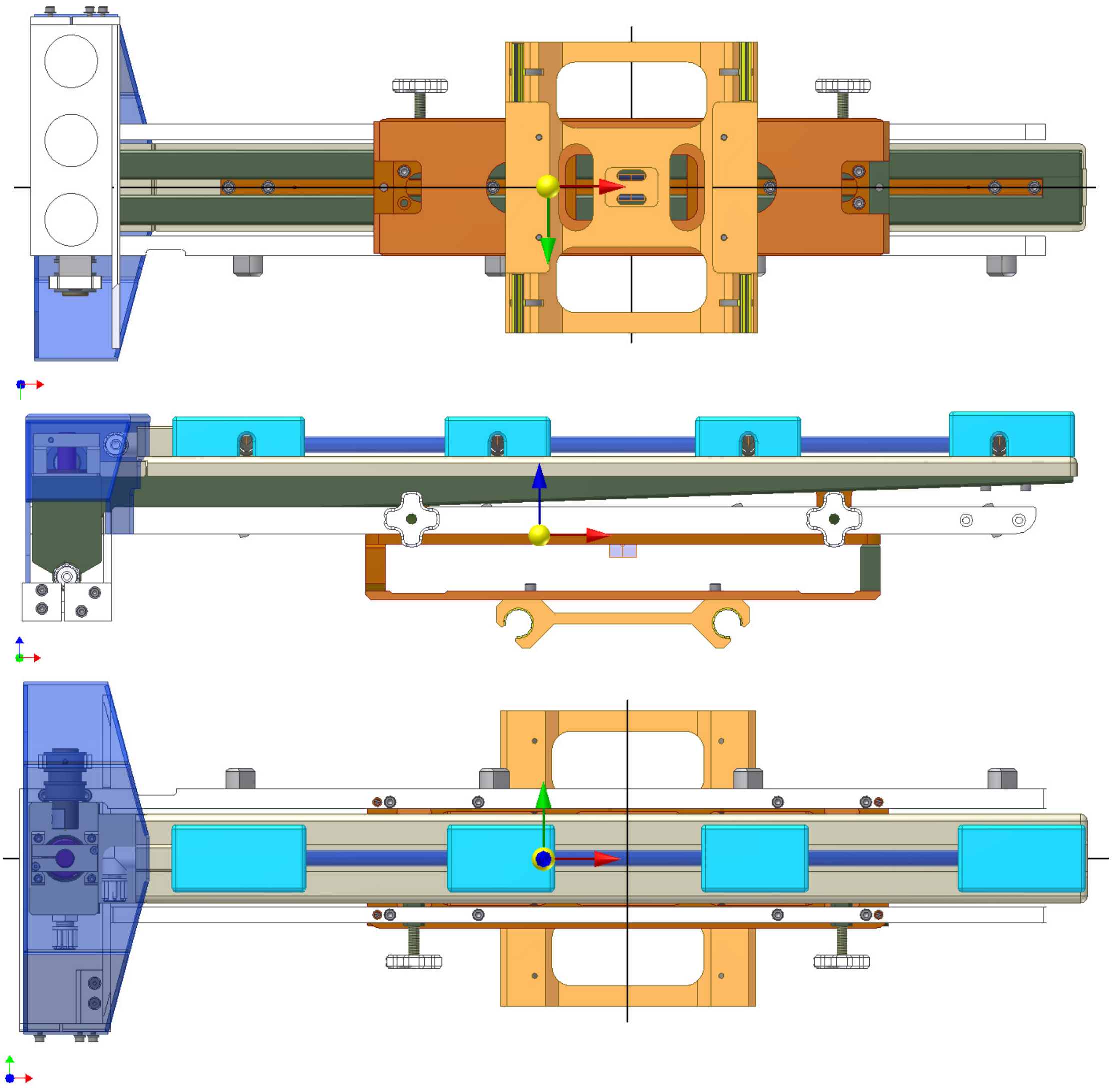


Picture 14: Design 333 optimization with counter weight

4.3.3. Carriage 333 with new head and without counter weight

Influence to COG by removing the counter weight at the end of the head led to reducing the total mass by 8,01 – 6,87 = 1,14kg and significant COG shifting in longitudinal direction up to 63,3mm compare to center of the head. This small design change can proceed substantial mass reduction in small design change of the guidance rail system position.

Total mass [kg]	Displacement compare to center of the head		
	X [mm] -red	Y [mm] - green	Z [mm] - blue
6,87	**-63,3**	**-0,5**	**6,6**

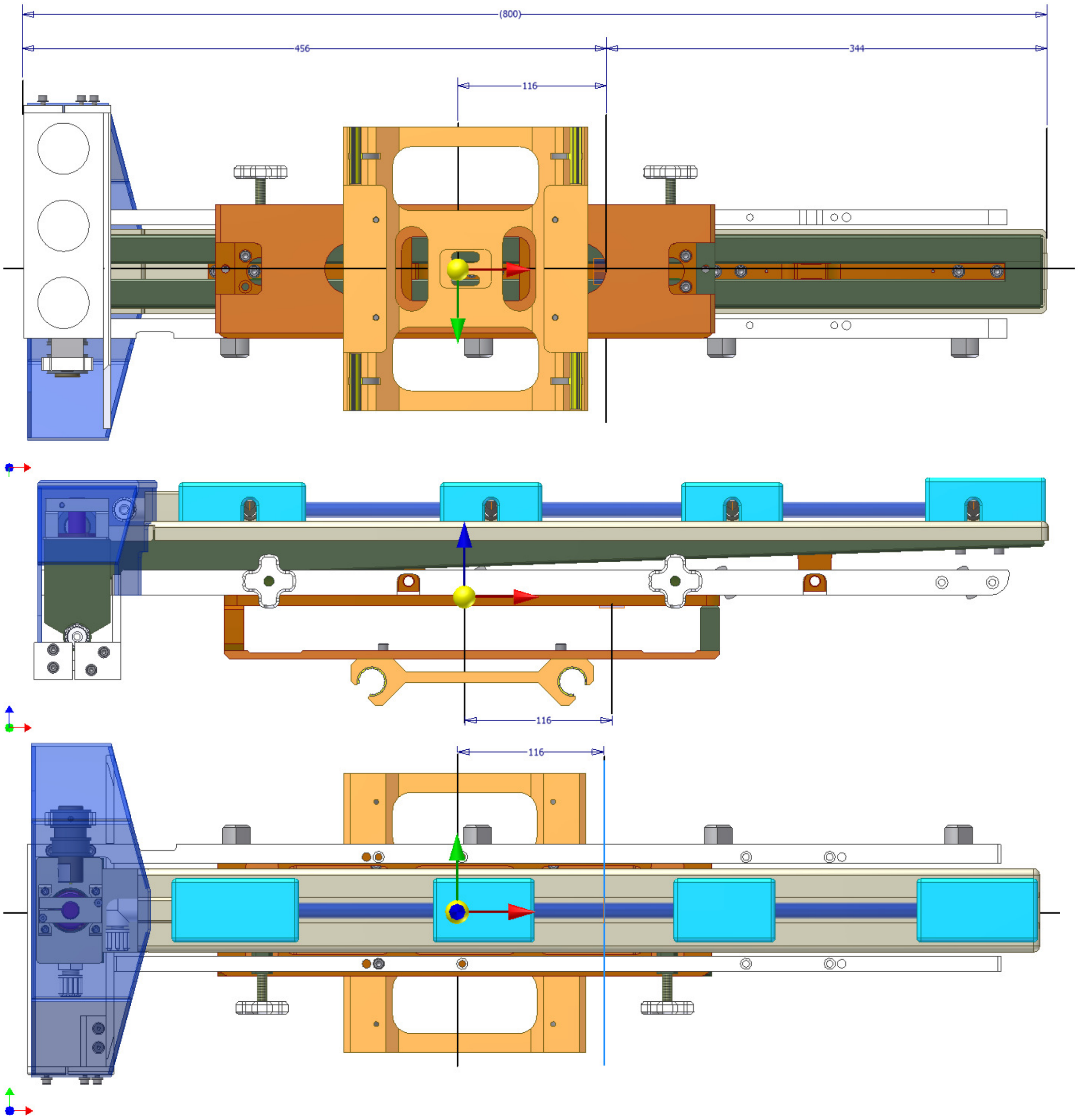


Picture 15: Design 333 optimization without counter weight

4.3.4. Carriage 333 with new head and without counter weight, distributed weight and optimized displacement

The optimization described in the chapter 4.3.3. was followed where the counter weight stayed removed and the carriage subassembly was moved in the longitudinal direction so the COG of the whole assembly will be in the center of belt connection. Consequently the total mass did not get changed and the value for the carriage movement is equal to 116mm.

Total mass [kg]	Displacement compare to center of the head		
	X [mm] -red	Y [mm] - green	Z [mm] - blue
6,87	**-116,0**	**-1,3**	**-1,4**

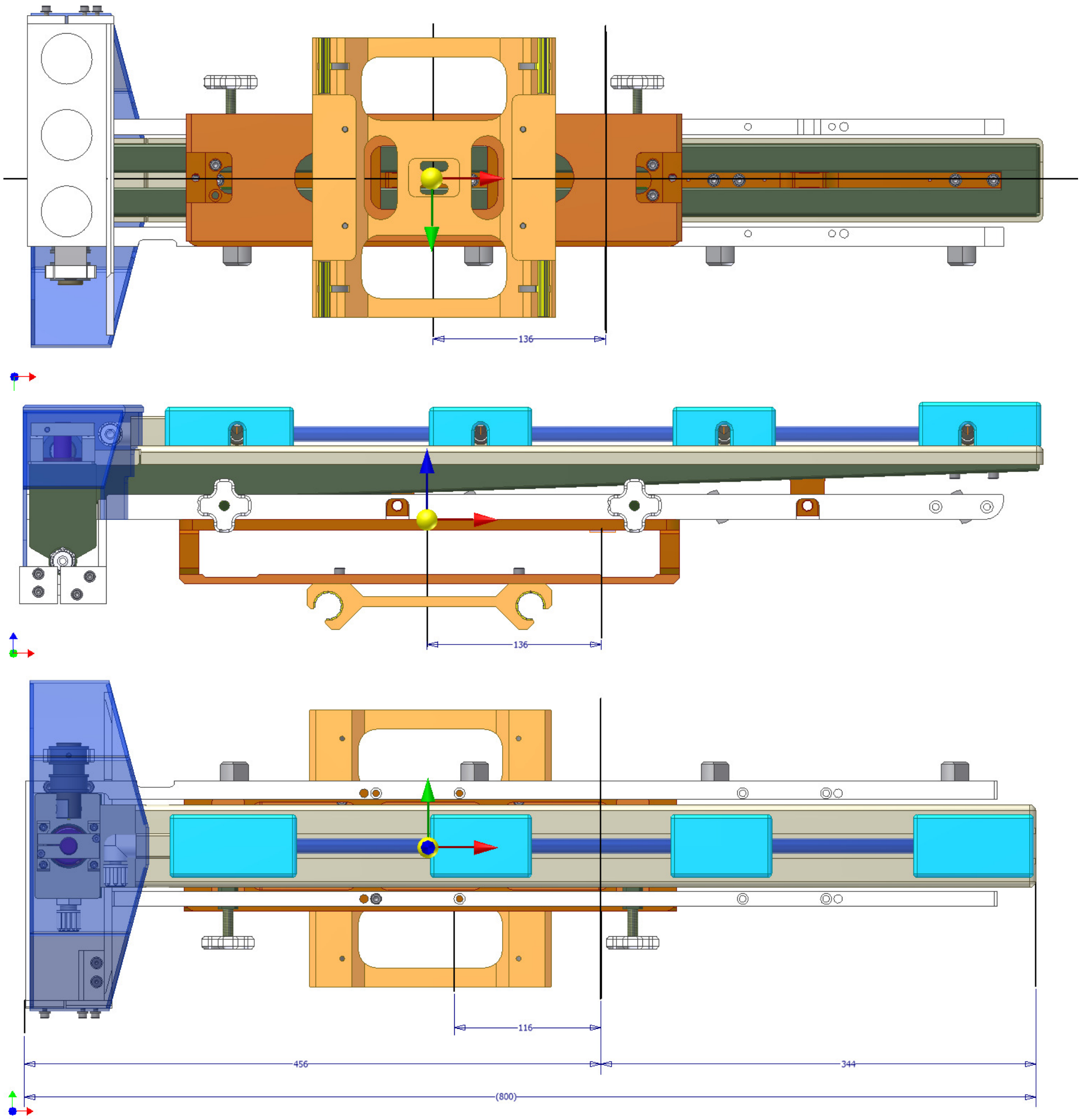


Picture 16: Design 333 optimization, optimized displacement

4.3.5. Carriage 333 with new head, without counter weight, changed side weight, distributed weight and optimized displacement

Final design change is to get rid of the stainless steel counter weight part at the lighter side of the carriage and substitute it with the same side part like on the other side. This design change express the highest mass savings compare to the previous design (see chap. 4.3.2.) 8,01 – 6,56 = 1,45kg with simple part removal. COG displacement compare to the previous one is in this case 136,6mm.

Total mass [kg]	Displacement compare to center of the head		
	X [mm] -red	Y [mm] - green	Z [mm] - blue
6,56	**-136,6**	**-1,2**	**-0,2**



Picture 17: Design 333 optimization, optimized displacement and mass

4.4. Evaluation of center of gravity optimization

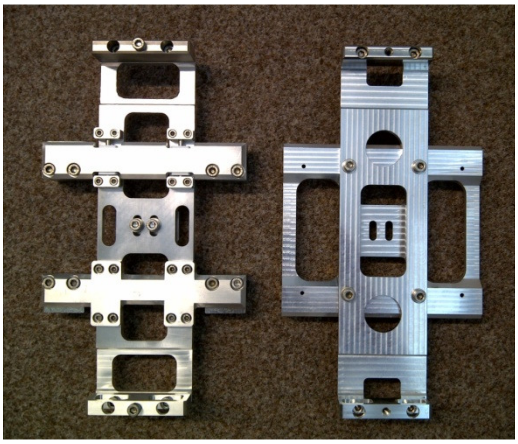
Irregular shape as well as use of several kinds of different materials in combination leads to target to reduce the weight as much as possible in order to lower down the loads on the assembly. The highest loading is from dynamic and friction forces caused by the mass, which can be improved specifically by reducing the total weight moving on the guidance rails (see Tab.8). Mass reduction allows faster and smoother movement of the whole linear guidance system. From this reason the counter weight was removed and the COG analyzed to get an ideal design of current assembly with changes into the system of the machine as less as possible. Table 8 bellow shows comparison of different optimization strategies processed in the chapters 4 above.

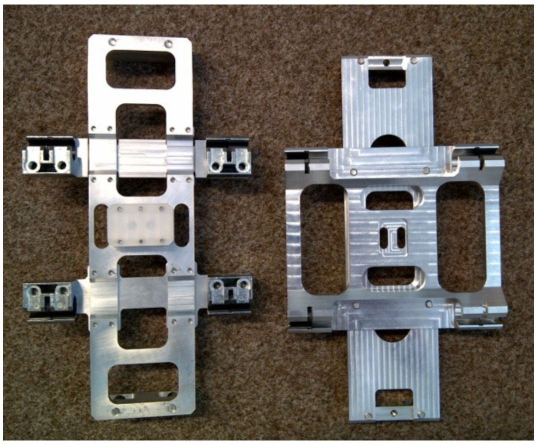
Table 8: Carriage-head mechanical assembly optimization

Optimi-zation	Description	Total mass [kg]	Displacement to the center of the head X [mm] - red	Y [mm] - green	Z [mm] - blue
4.3.1.	111 with CW	8,15	-11,2	-0,4	9,4
	new head				
Pic. 3	111 without head	2,62	-24,7	0,82	-36,8
	without top part				
Pic. 4	333 without head	2,44	24,7	2,1	-46,5
	without top part				
4.3.2.	333 with CW	**8,01**	-12,3	-0,4	8,1
	current placement				
4.3.3.	333 without CW	6,87	-63,3	-0,5	6,6
	current placement				
4.3.4.	333 without CW	6,87	-116	-1,3	-1,4
	distributed weight				
	optimized displ.				
4.3.5.	333 without CW	**6,56**	-136,6	-1,2	-0,2
	changed side part				
	distributed weight				
	optimized displ.				
Total weight saving due optimization		**1,45**			
Need to move carriage compare to present design			**-124,3**	-0,8	-8,3
Comparison of optimized 333 assembly to 111 old design with new head					
Total weight saving due optimization		**1,59**			
Need to move carriage compare to present design			-125,4	-0,8	-9,6

Optimization in the chapters 4.3.2. and 4.3.5. show that it is possible to lighten the head and carriage subassembly for another 1,45kg at least. To have proper belt connection the carriage had to be moved nearly 125mm in X longitudinal direction compare to current design in order to be as close as possible above the COG of the whole system leading to the ideal position.

With FEM optimization of the 333 carriage the weight will be further reduced for the limits in the material strains as well as the head connection bar design and the side bars has to be changed with length reduction not needed as seen from the optimization. The FEM calculations will prove at the optimized model feasibility of the design with keeping or reducing of the same loading on the subassembly as well as significant mass reduction. This design changes brings input to the machines from the point of view of better application and smoother movement without jerky mistakes, however certain changes must be made in the design of subassembly of the machine, which are not substantial to the design of the whole machine. Assembling time of the whole subassembly will be lower since the amount of parts reduction was achieved and bolted connection diminished. Further reduction in vibrations will have positive impact in the machine structure and noise point of view. Vibrations transferred into the aluminum construction of the machine will improve the long term stability of the frame and feasibility of other particular subassemblies in the machine.





Picture 18: Manufactured design 111(left) and 333 (right)

At the picture above can be seen manufactured proposed designs 111 and 333, which were furthermore tested in the company. Design 333 showed in testing better functionality with lower vibrations and jerky movements and therefore was decided to follow specifically design 333 and optimize it to the lowest mass with the same or lower stiffness up to ¼ of the aluminum alloy properties. Meaning that from approximately 450MPa the stiffness can go up to 125MPa after loading, which was decided in research and development center of the company, based on the engineering experience and common decision design rules.

For FEM analysis will be used assigned actually used materials as stainless steel, aluminum alloy and polypropylene. Module ProMechanica in ProEngineer in version Wildfire 5 uses linear models for its calculations with improved meshing for viscoelastic materials. Due to this fact plastic material as polypropylene which in reality performs nonlinear strains is simplified in this analysis into the linear model for viscoelastic behavior. Thus a small mistake is brought into the model, but is not critical for models in this work and the model meshing is sufficient with trustworthy deviation in the results. The results are achieved with multi pass automatic software functions, which are recalculating the equations sets several times up to the point when the convergence is close to the continuous solution.

5 STIFFNESS CALCULATION OF CURRENT LINEAR GUIDANCE SYSTEMS WITH USE OF FEM

Stiffness calculations were made as described in the optimization chapter 4 as well as boundary conditions and load assessment proceeded according to assemblies separation in the table 2. Therefore further the mechanical assemblies are assessed in three different groups relevantly to their loading. It is considered that a correctly designed and installed synchronous belt drive should operate successfully for between 8000 and 12000 hrs and have an operating efficiency of about 98%.

Although this composition is a dynamic character it can be reassigned to the statically loaded task with minor assumptions. Meaning that instead of concluding dynamically moving parts it was taken from opposite point of view to the static assignment. In place where would affect the belt drive the assembly by the acceleration there will be boundary conditions as well as on linear guidance system where the carriage is supported on the linear rods. The loads then will be prescribed in opposite direction of actual assembly movement. From acceleration measurements (Chap. 3.1.) and overview about the highest loading of the carriage was decided that this is the way of finding out the highest stress von misses and displacement in different parts of the assembly, because that will be the case of highest loading. All parts from the assembly are read into the Pro-Mechanica Pro-Engineer software environment as bonded model, where in places of bolt connection is considered full material. For FEM calculation was used a mesh which included for all models around 600 000 elements (for details see enclosed DVD). Contact connections are not taken into account since aluminum alloys are sufficiently sturdy parts bolted connections are considered as full material. As well as sliding plastic bearings on the carriage transforming the acceleration into the whole assembly are considered as bonded model along with the fact that it is the place for assigning the friction forces.

<u>Forces loading set assignment for mechanical assemblies 111-333:</u>

Maximum load from the belt conversion to the carriage connection =

Active forces + Energy chain horizontal forces + Friction forces

F_max_base = 12*10 + 10 + 12*9,81*0,1 = 120 + 10 + 11,8 = 141,8 N (11)

F_max = F_max_base * 0,98 belt efficiency = 138,9 N (12)

F_vertical = gravity load = m * 9,81 = 12*9,81 = 117,8 N (13)

F_en_ch_horizontal = 10 N (14)

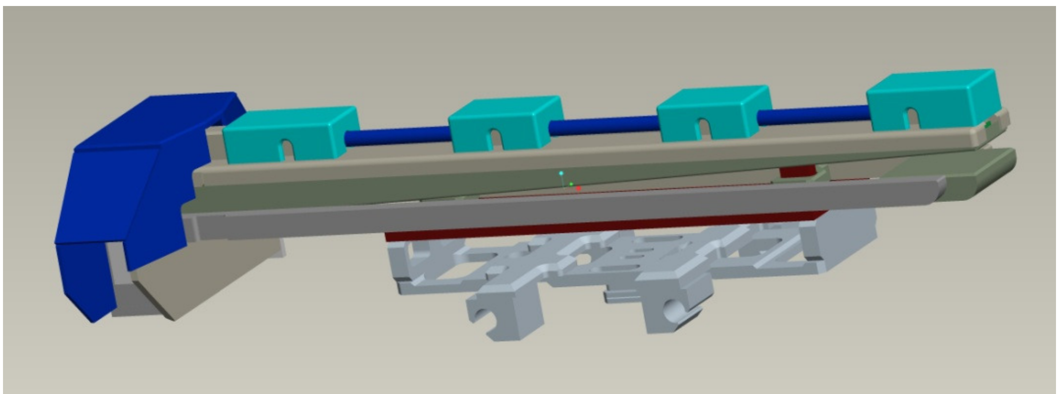
F_en_ch_vertical = 5 N (15)

Friction loading was applied to the static model from the formula 8 applied as the highest dynamical loading from the moving mass by the belt as well as the forces from the energy chain.

5.1. FEM calculations for mechanical assembly 111

This assembly was used as the oldest version of the design in the first family of nanotechnology machines. It is the most complicated and heaviest dynamically moving assembly and therefore it will be used for load calculations applied also in other lightweight subassemblies as reference. Respectively the other carriages will be slightly overloaded than in reality, but it will assure that the concept is feasible and trustable as well as it will be understood what was happening in the concept after the eventual warranty claim. Critical factor needed to be observed is the die on head displacement.

Screw mounted carriage 111 is used and nanotechnological head which has parts later lightened in other designs. This design provided several troubles including high vibrations and jerky movement after the machine transport to the costumer. Therefore FEM calculations supposed to assist understanding what was happening in that design.



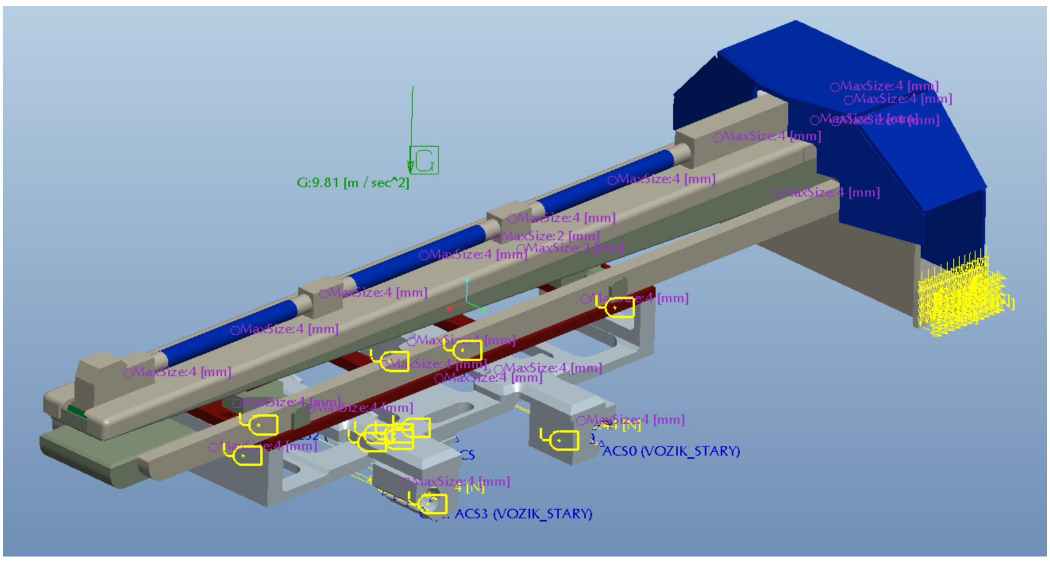
Picture 19: Mechanical assembly 111

FEM calculations of this assembly were used only to get overview and values for the load behaviour of similar assemblies in order to compare them. This kind of carriage is not used in the new generations of the nanotechnology machine, but these results are used as reference to the potential problems occurring in the future working life of this functional part as well as reference with which additional subassemblies it can be replaced.

Table 9: Design 111 FEM load assessment

Weight of the moving assembly	**12**	kg
Maximum acceleration from the measurements	**5**	m/s2
Linear movement length	**1600**	mm
Time for crossing of one path	**1,6**	s
A velocity profile 800mm acceleration	**0,8**	s
A velocity profile 800mm deceleration	**0,8**	s
Idle time in reversible movement	0,25	**s**

The table 9 above describes the conditions used in the setting up of the movement as well as it express that the "A" working distance profile was used, which consider the half of the traveling distance acceleration and the second half deceleration of the carriage. Furthermore the boundary conditions were assigned bellow and the assignment can be seen on the picture 20 also with the loading forces. The energy chain connection is at the right place of nanotechnological head (see yellow forces on Pic.20).



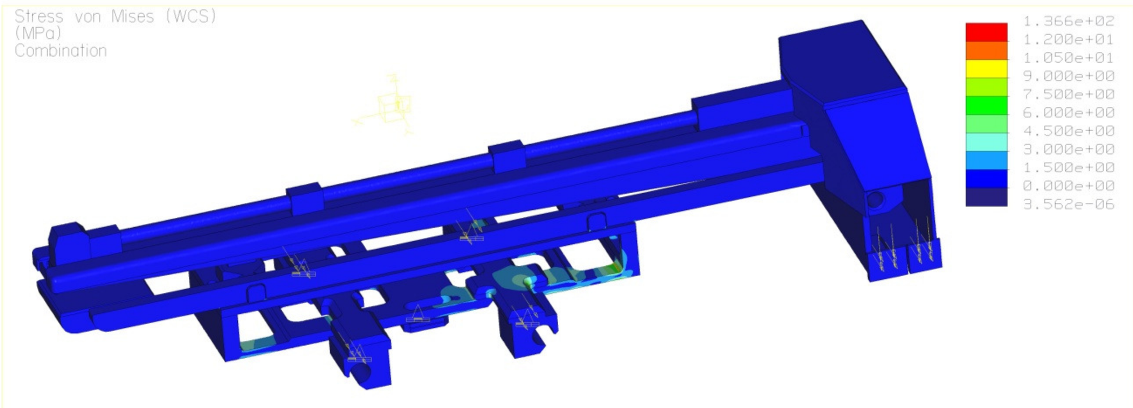
Picture 20: Mechanical assembly 111 with boundary conditions asignment

Boundary conditions for FEM calculations:

All loads to the assembly were considered as reaction forces in opposite direction to the movement according to the static reassignment of the task. Therefore meaning is that the dynamic task was changed into the static assignment in the worst case assuring that the assembly endures the loading. Acceleration forces were assigned to the COG together with gravity load forcing the whole assembly model. Energy chain load was assigned on the plane as horizontal and vertical surface force at the energy chain connection plate. Boundary conditions are assigned that the belt connection is stable and the carriage is sitting on cylindrical system in each of the frictional bearing which cannot also change rigid vertical position but can slide only instead.

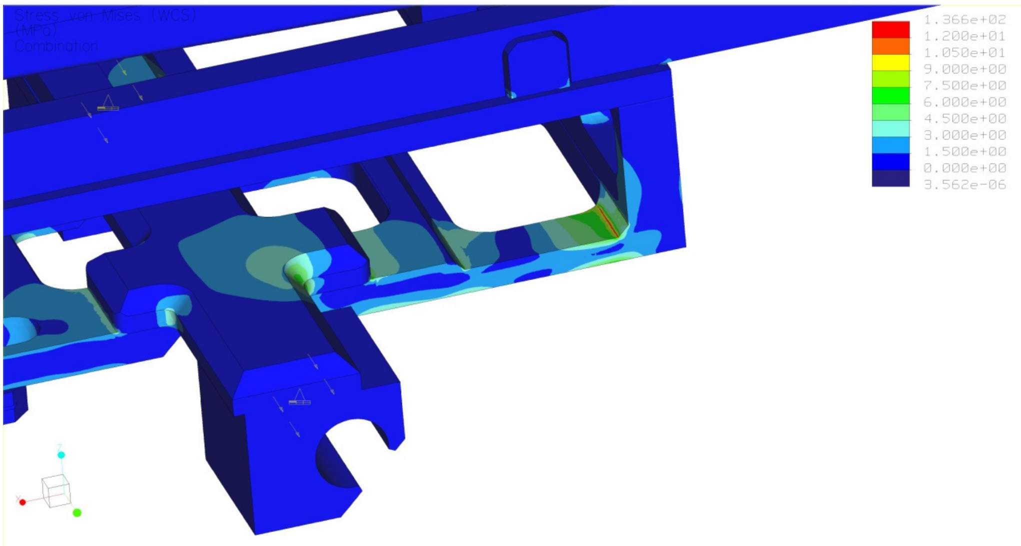
Therefore frictional force on each frictional bearing is equal to ¼ of F_max:

F_max_1bearing = F_max / 4bearings = 138,9 N / 4 = 34,8 N **(16)**



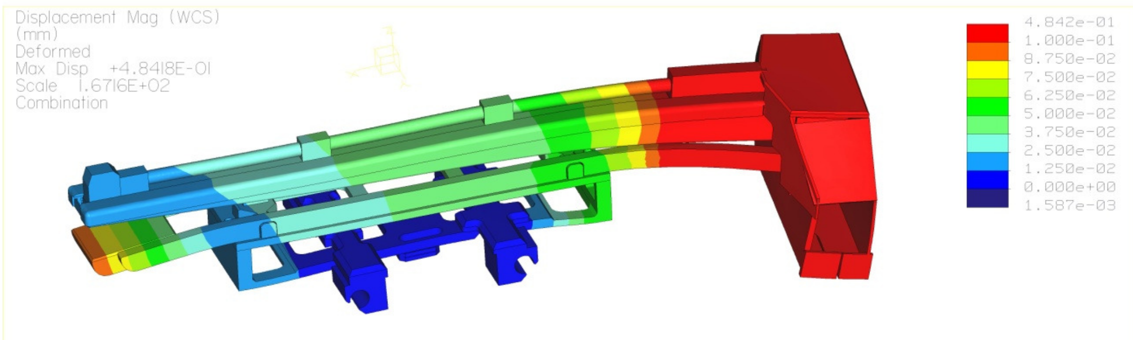
Picture 21: Mechanical Assembly 111 Stress Von Misses (ISO view)

The FEM analysis showed that this oldest design 111 was unhappily designed so that the places evincing the highest stress loading are exactly at the places where the designer chose lightening of the carriage (see Pic.21). More precisely the highest stress Von Misses 136MPa in the red color is observed at the edge of lightening by the sideboard (see detail on Pic.22). Furthermore all sharp edges on the lightening of this bolted carriage are not luckily strained, which also during the working life also applies the strains to the screws assuring the accuracy of the guiding system including the part holding the friction bearing housing. Right site of the carriage is more loaded due to the fact of extra forces from the energy chain (see Pic.21).



Picture 22: Mechanical Assembly 111 Stress Von Misses (detailed view)

Maximal displacement on this assembly was calculated as 0,48mm at most of the plastic parts of the nanotechnological head (on the right of Pic.23). Other parts of the head shows displacement around 0,1mm, where the counter weight creates the highest loading at the end of the head. It can be seen that the carriage design 111 is highly oversized and does not evince nearly any positive displacement but on the other hand bad construction allocate in the design the highest stress at the edges. Maximal die displacement 0,48mm is at the one closest to the energy chain connection.

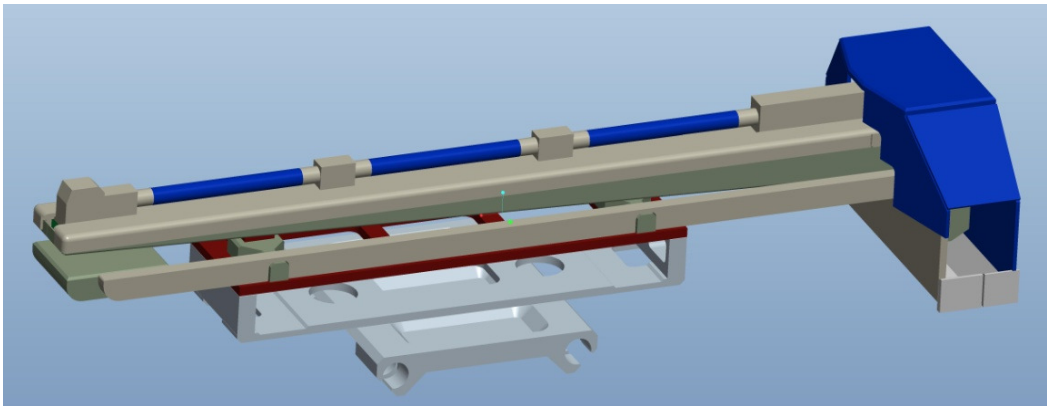


Picture 23: Mechanical Assembly 111 displacement

Total mass assigned in the 3D model according to the used material as well as including the polymeric fluid in the supply hoses was 11,3kg, which is due to simplification of some models and not including some insignificant parts as f. e. covers of the retarders. More detailed views of calculation results for stress as well as for displacement values can be found in the appendix 1.

5.2. FEM calculations for mechanical assembly 222

Mechanical parts used in this assembly is a new design of the carriage and new lightened head compare to the design 111, which allowed to reduce the whole weight of the head compare to old head used in the design 111 by 2kg. New design of the head as well as carriage design 222 substantially reduced the amount of parts, reduced the time needed for assembling and setting up the guidance system (see Pic.24). Therefore supposedly the reactions, stiffness and displacement must be lower with assumption of the same loading as assembly 111 (described in chap. 5.1.).

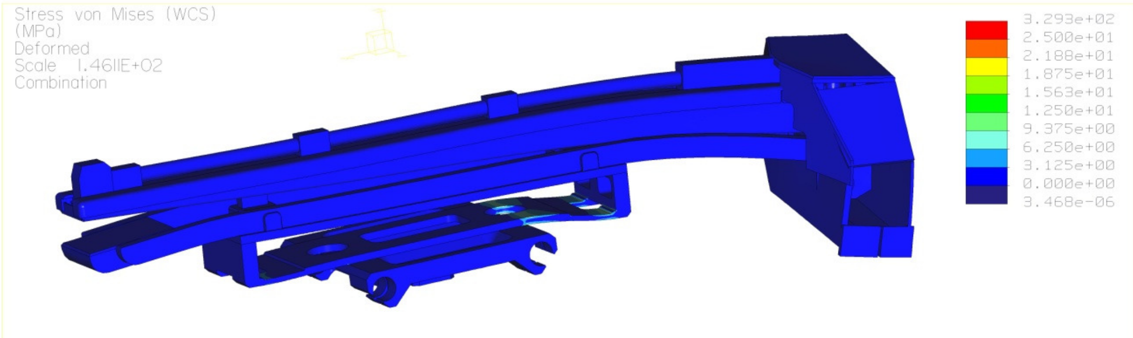


Picture 24: Mechanical assembly 222

In the table 10 is seen usage in the setting up of the movement as well as it express that the "A" working distance profile also used in the preliminary design 111, which considers the half of the traveling distance acceleration and the second half deceleration of the carriage. Boundary conditions were assigned in the prescribed standard referencing the design 111 with the different of having new light weighted head and different carriage design 222 (Pic.24), which did not save much of the mass.

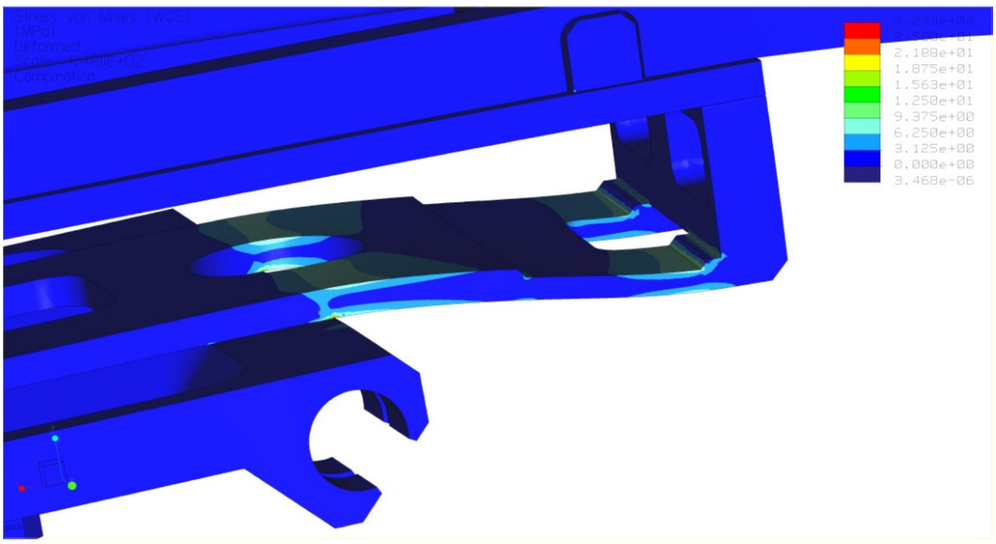
Table 10: Design 222 FEM load assessment

Weight of the moving assembly	10	kg
Maximum acceleration from the measurements	5	m/s2
Linear movement length	1600	mm
Time for crossing of one path	1,6	s
A velocity profile 800mm acceleration	0,8	s
A velocity profile 800mm deceleration	0,8	s
Idle time in reversible movement	**0,25**	**s**

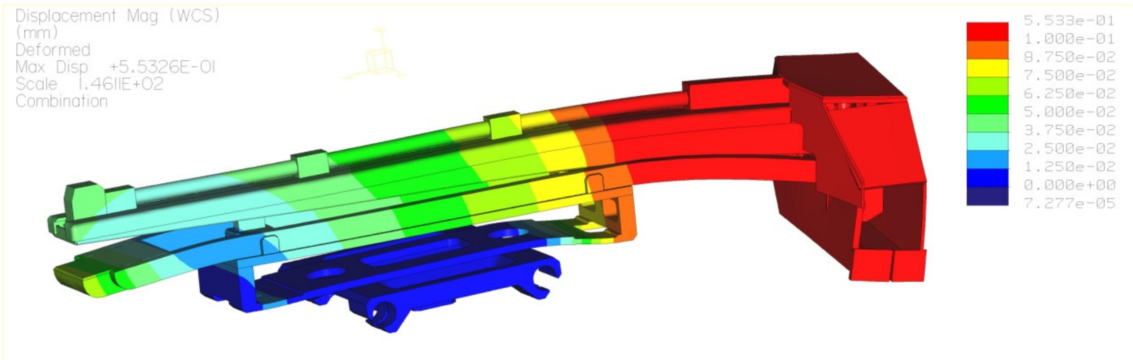


Picture 25: Mechanical Assembly 222 Stress Von Misses (ISO view)

The FEM analysis showed that the new design 222 solves only partially the stress problem of the assembly and moved the loading to the plastic parts instead. The highest stress Von Misses analyzed was in the connection of plastic peaces under the blue cover and can be considered as irrelevant. More precisely the highest stress Von Misses 187MPa in the dark green color is observed at the edge of the new base plate lightening by the sideboard (see detail on Pic.26) as well as at the edge of the carriage and the new base plate directly bolted to that. Furthermore all sharp edges on the lightening of this carriage are not well strained. The circular lightening of the base plate actually allows spreading of the stress in the carriage, which also applies the strains to the accuracy of the guiding system. The friction bearing housing in case will be very rigid and in case of out parallelism of the guidance rods it can get stuck. Right site of the carriage tends to twist to the site of energy chain connection (see Pic.25).



Picture 26: Mechanical Assembly 222 Stress Von Misses (detailed view)



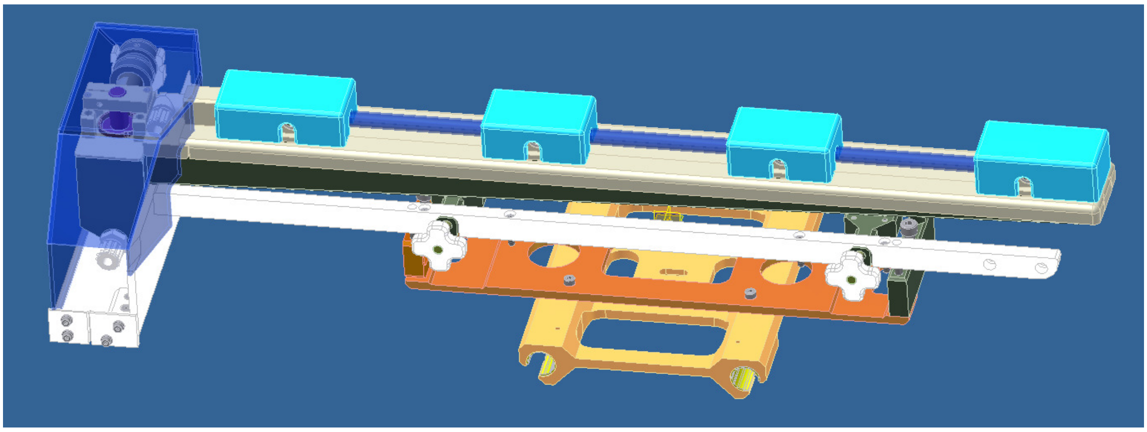
Picture 27: Mechanical Assembly 222 displacement

Maximal displacement on this assembly was calculated as 0,55mm at most of the plastic parts of the nanotechnological head at the energy chain connection (on the right of Pic.27). Other parts of the head shows displacement around 0,06mm and it can be observed that the carriage design 222 is highly oversized and can be further light weighted. Solid carriage design does not evince nearly any positive displacement but on the other hand bad base plate construction allocate in the design the highest stress at the edges of lightening and sideboard with displacement around 0,1mm. Maximal die displacement 0,53mm is at the one closest to the energy chain connection.

Total mass assigned in the 3D model according to the used material as well as including the polymeric fluid in the supply hoses was 11,7kg, which is 0,4kg more compare to the design 111 due to the solid construction of the carriage and keeping all other parts excluding the new base plate. More detailed views of calculation results for stress as well as for displacement values can be found in the appendix 2.

5.3. FEM calculations for mechanical assembly 333

Latest version of new carriage and head design consists from the same lightened head like in the design 222 and new design of carriage with reduced weight from design 222 (see Pic.22), where all friction bearings are installed in one part assuring linearity in the guidance system. Mass is further reduced in this design and therefore there is expectation for future usage of this carriage and optimization to agreed stiffness resulting in other mass reduction. However the mass saving compare to the design 111 is only 0,18kg it brought new promising concept of the carriage design (see Pic.28).



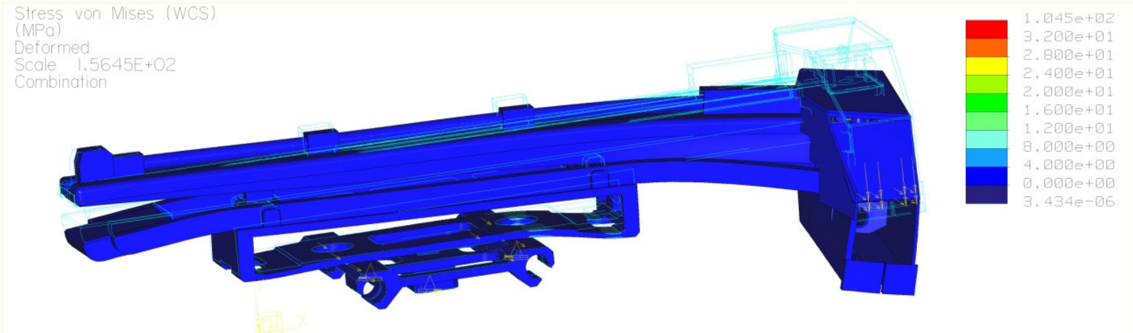
Picture 28: Mechanical assembly 333

Table 11 bellow express the same standard usage setting as previous designs and is set up for movement in “A” working distance profile, which considers the half of the traveling distance acceleration and the second half deceleration of the carriage. Light weighted head was used and the change in the design brought mass reduction by 0,5kg compare to the design 222.

Table 11: Design 333 FEM load assessment

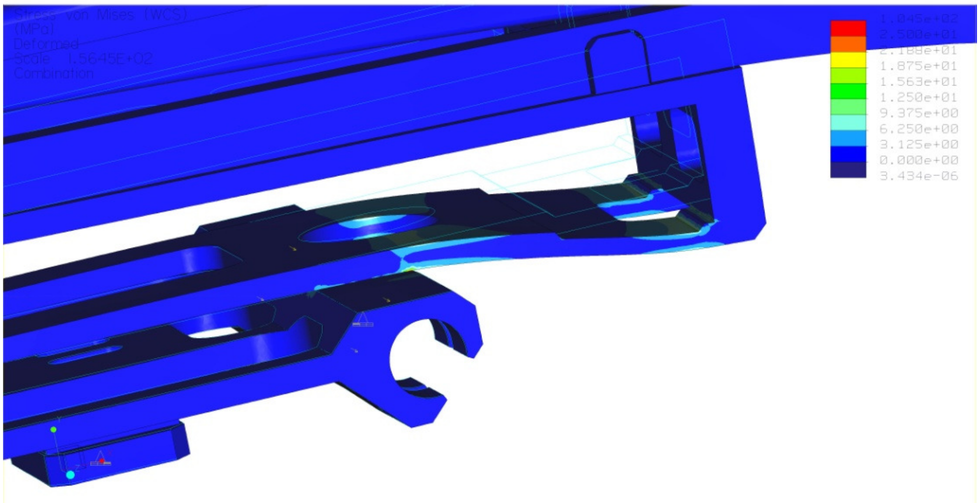
Weight of the moving assembly	9,5	kg
Maximum acceleration from the measurements	5	m/s2
Linear movement length	1600	mm
Time for crossing of one path	1,6	s
A velocity profile 800mm acceleration	0,8	s
A velocity profile 800mm deceleration	0,8	s
Idle time in reversible movement	**0,25**	**s**

The FEM analysis showed that the design 333 (Pic.28) expresses much higher malleability compare to the design 222 resulting into much lower stress in the assembly. It solves the stress problem of the assembly in plastic parts and turn down the stress on the base plate. Loading will go expectably to the guidance rods trough the friction bearings. Dispersing the stress profile across bigger volume improve the stability of the assembly (see Pic.29). However the highest stress Von Misses 105MPa analyzed was again in the connection of plastic pieces mostly and at the edge of the base plate. Other common stress in the carriage is under dark green color expressing stress around 25MPa (see Pic30).



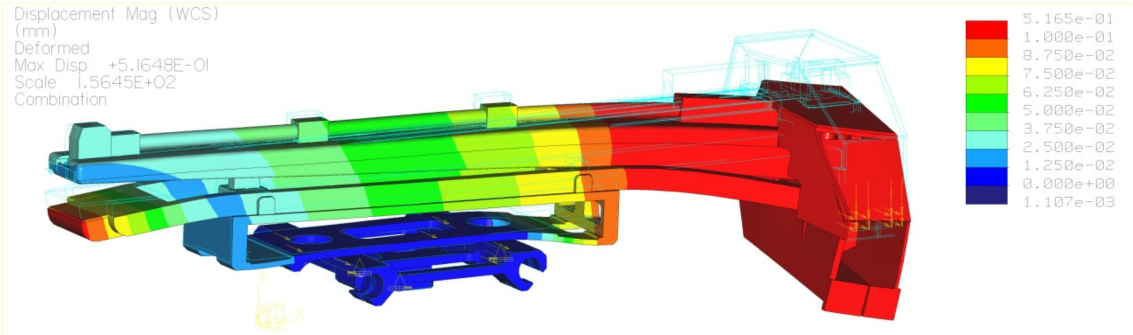
Picture 29: Mechanical Assembly 333 original Stress Von Misses

The friction bearing housing in this case will be still very rigid and keeping the parallelism of the guidance rods with better malleability for misalignments. Sites of the carriage tend to twist to the direction of movement (see Pic.29).



Picture 30: Mechanical Assembly 333 original Stress Von Misses (detailed view)

Maximal displacement of this assembly was calculated as 0,52mm at most of the plastic parts of the nanotechnological head at the energy chain connection and also the counter weight (on the right of Pic.31). Value of the maximal displacement does not change much compare to the previous designs because of the reaction forces on assembly placement. Other parts of the head show displacement around 0,07mm and it can be observed that the carriage design 333 is now also loaded compare to the design 222 where was evident over sizing. Displacement distribution does not vary to previous design, which is caused especially thanks to the COG of the whole assembly and loading out of that. Therefore further computations will be made according to optimization.

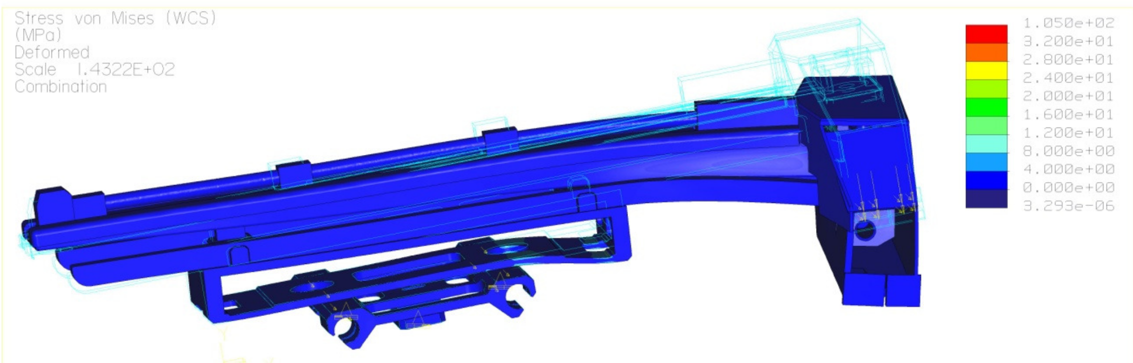


Picture 31: Mechanical Assembly 333 original displacement

Mass of this design was reduced by 0,5kg compare to design 222 by the carriage lightening and total mass assigned in the 3D model according to the used material as well as including the polymeric fluid in the supply hoses was finally 11,2kg. Other detailed views of calculation results for stress as well as for displacement values can be found in the appendix 3. Maximal die displacement 0,51mm is at the one closest to the energy chain connection.

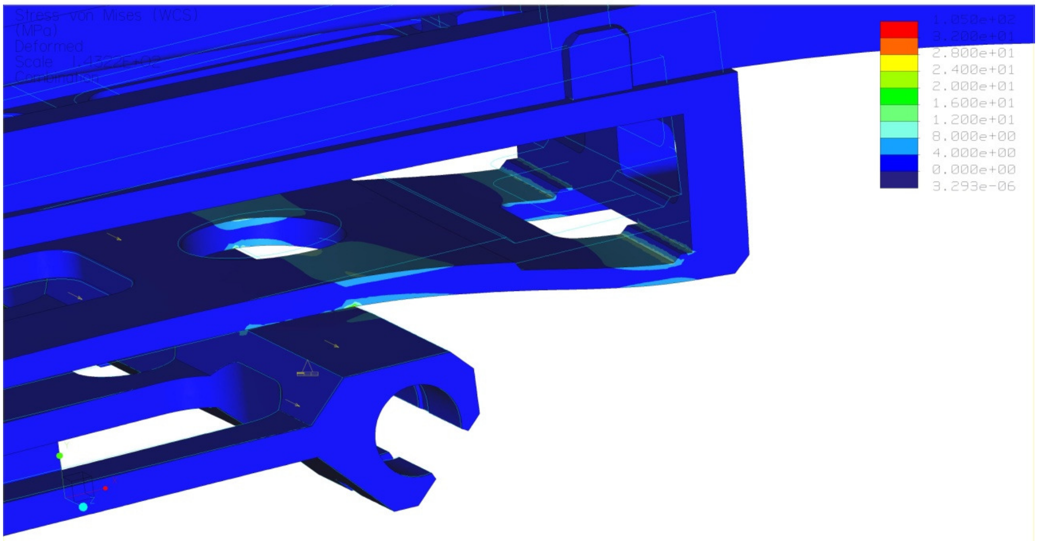
5.4. Mechanical assembly 333 without the counter weight (WCW)

Following up the promising design 333 was tested what will happen after removing the counter weight from stainless steel which can significantly reduce the total mass by 1,3kg. Predictably the center of gravity got much further from the center of the belt connection and will cause higher loading on the friction bearing or even cause blocking of the carriage due to the lateral loading and jerky movements.



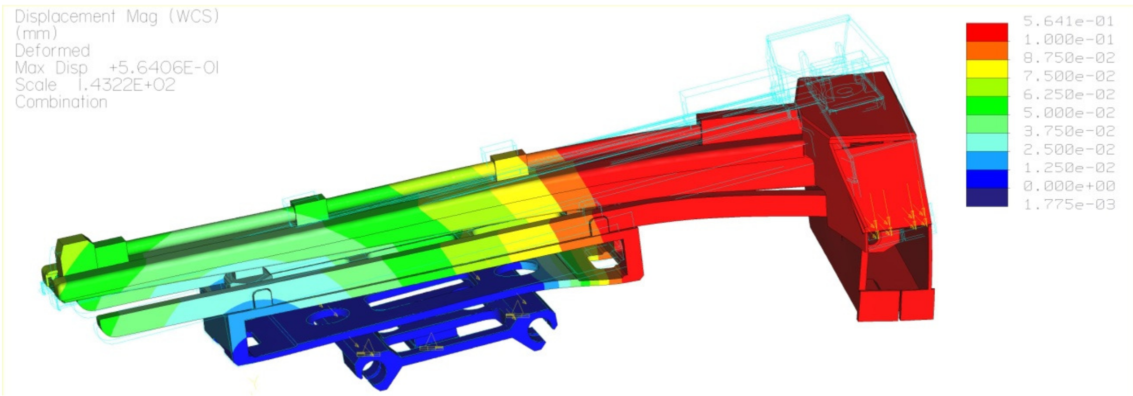
Picture 32: Mechanical Assembly 333 WCW Stress Von Misses

Maximal stress Von Misses 105MPa compare to the design 333 with attached counter weight did not change due to the fact that these strains are at the plastic pieces at the belt connection site (see Pic.32). However stress observed at the highest loaded part on base plate of the carriage decreased to around 20Mpa in much smaller areas. Results lead into the fact that the counter weight removal does not help to decrease strains in the carriage, but just helps lower deformation of the assembly (see Pic.33).



Picture 33: Mechanical Assembly 333 WCW Stress Von Misses (detailed view)

Maximal displacement of this assembly was calculated as 0,56mm, which was here now even on the sideboard of the carriage due to the counter weight removal. This move allowed higher loading of the right side of the carriage and has negative impact on the movement stability and repeatability. Value of the maximal displacement does not change much compare to the previous design especially because of the reaction forces on assembly placement and the assembly COG position (see Pic.34).



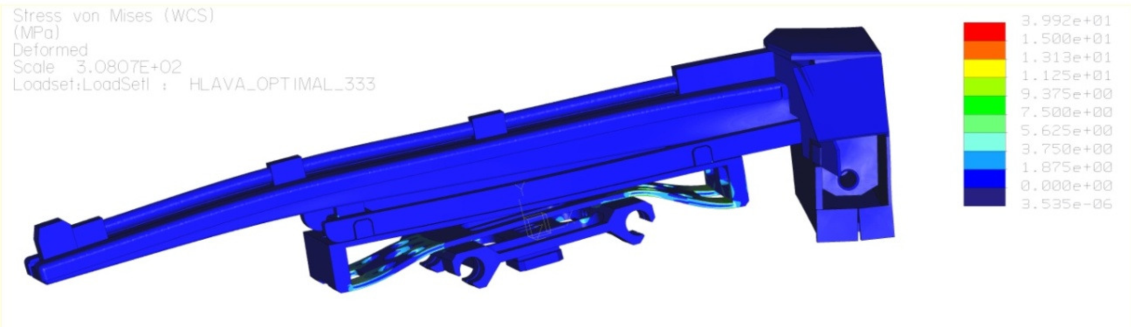
Picture 34: Mechanical Assembly 333 WCW displacement

Therefore other parts of the head show displacement around 0,07mm and it can be observed that the carriage design 333 is now also loaded much more compare to the previous design 333 with the counter weight. Displacement distribution does not vary to previous design, which is caused especially thanks to the COG of the whole assembly and loading out of that. Therefore further computations will be made according to optimization and the ideal COG of the assembly and center of the timing belt will be analyzed (optimization made in Chap.4.3.5). Maximal die displacement 0,56mm is at the one closest to the energy chain connection.

Mass of this design was drastically reduced by 1,3kg compare to previous design 333 by removing the counter weight. Giving that the 3D model was 9,9kg according to the used material as well as including the polymeric fluid in the supply hoses. Other detailed views of calculation results for stress as well as for displacement values can be found in the appendix 4.

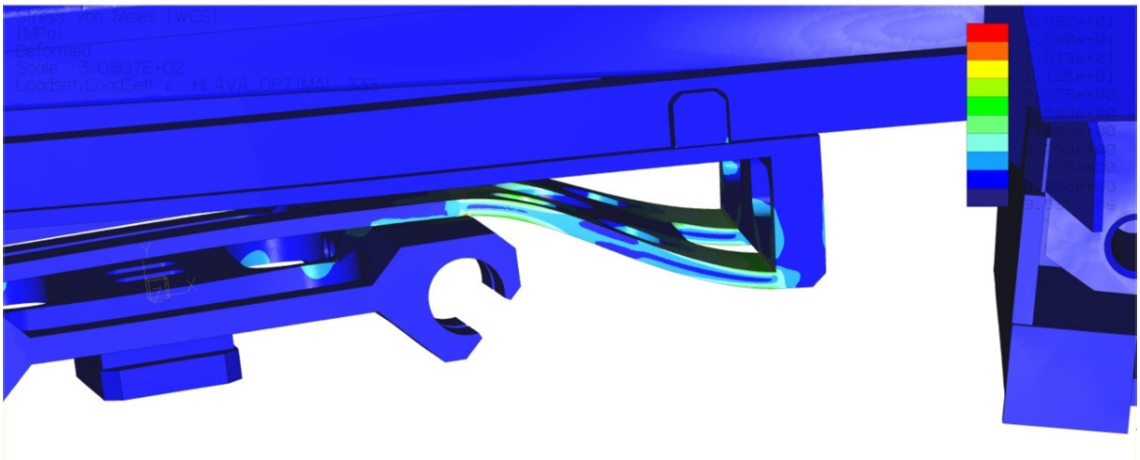
5.5. Mechanical assembly 333 with optimized COG

This is proposed design change of the current carriage and head design, which expresses the total mass reduction by 2,3kg compare to preliminary design 111. It is using the new light weighted head, counter weight was removed and the holding bars were shortened. The total mass including fully supplied hoses with polymeric fluid is 9kg. Furthermore the top and bottom base plates have been optimized by reducing their thickness to 5mm and lightening according to previous experience from the FEM calculations. This optimization steps means that it requires minimal change of the whole machine design, but it assure higher quality work ability with lower loading of all of the assembly parts.



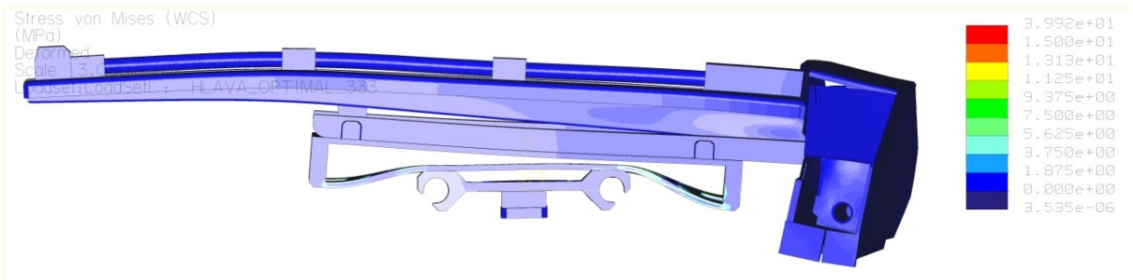
Picture 35: Mechanical Assembly 333 optimized Stress Von Misses

Change of the carriage position and placing the center of the belt connection under the COG of the whole assembly drastically diminished the stress Von Misses to the maximum 39MPa found again at plastic parts connection close to the energy chain and the sharp edges of connecting parts with the bottom base plate (see Pic.35).

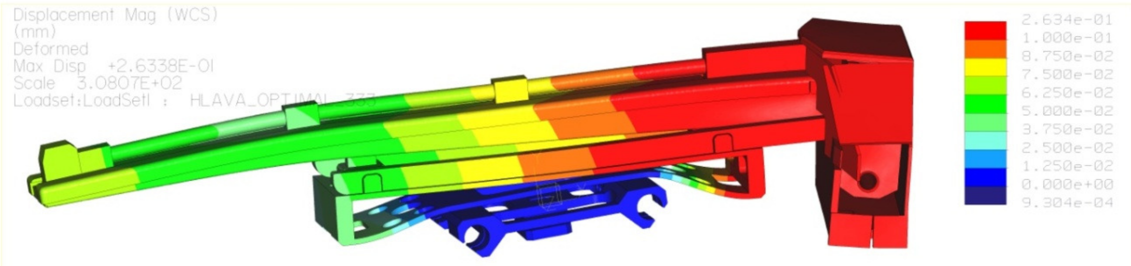


Picture 36: Mechanical Assembly 333 optimized Stress Von Misses (detailed view)

However the analyses show the maximum stress 39MPa the bottom base plate have in the optimized shape at most of the places only around 12MPa and transferring more some of the loading into the carriage (see Pic.36). Deformed shape of the assembly shows eventual assembly loading which is not more transferred into the malleability of the base plate and the carriage by adding extra holes in the middle of the body. Moving the carriage to the COG of the whole assembly also optimized even deformation of the whole assembly and so this change will decrease the load on the wire while movement and nanofibering process. It is important that the retarders stay in line and decrease the tension in the wire (see Pic.37).



Picture 37: Mechanical Assembly 333 optimized Stress Von Misses (front view)



Picture 38: Mechanical Assembly 333 optimized displacement

The maximal displacement was rapidly reduced to the half compare to the previous designs thanks to optimization of the COG and is reaching at half of the assembly value 0,26mm (see Pic.38). As well as that the maximal die displacement was reduced to the 0,26mm. This displacement is caused by the energy chain connection and the highest loading on the carriage is again on the sideboard and closer end of the bottom base plate. Rest of the assembly is moving with the displacement around 0,06mm but with carriage rigidity keeping. Other detailed views of calculation results for stress as well as for displacement values can be found in the appendix 5.

5.6. FEM calculations evaluation

Analysis for all three proposed designs were made as well as the best solution was chosen according to engineering aspects. As appropriate design was chosen the design 333 which was also optimized for lowest mass and the proposed changes were analyzed (see Chap.5.5.). Feasibility of the carriage design was controlled. Simplicity together with price was taken into account and at the end the simplicity of assembling and maintenance. Chapters 5.1. – 5.5. provide detailed description about the results of the particular analysis and further result views can be seen in the appendix 1-5.

Table 12: FEM analysis evaluation

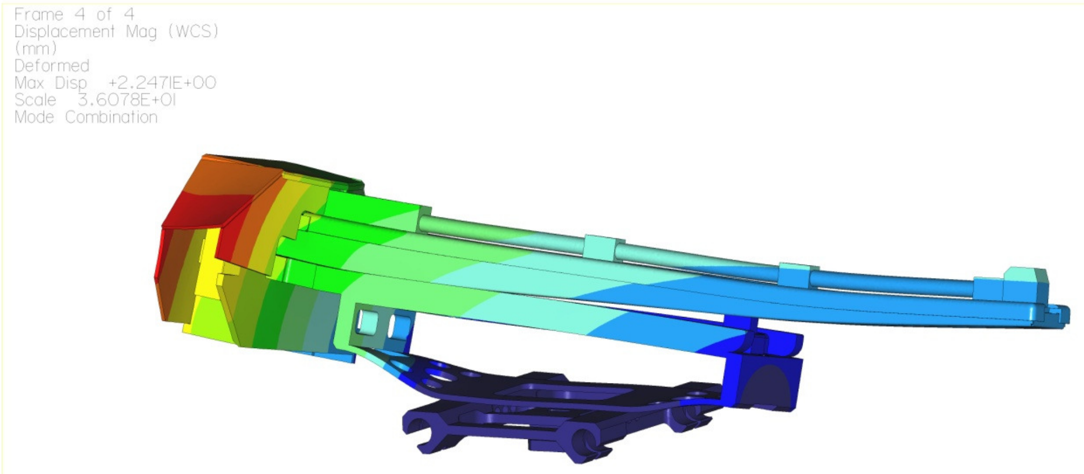
Design	Max. Stress [Mpa]	Max. Displacement [mm]	Assembly Weight [kg]
111	136	0,48	11,3
222	187	0,55	11,7
333 original	105	0,52	11,2
333 without counter weight	105	0,56	9,9
333 optimized COG	**39**	**0,26**	**9**

All three first designs showed very similar results in maximal displacement around 0,50mm as well as total mass is in the range of +/- 0,5kg. Maximum stress Von Misses value differs due to different malleability of the carriage. All of them have the same loading and stress changes because COG of the carriage is out of the central COG of the whole assembly. The design 222 expressed the highest stress, because it is the most rigid design (see Tab.12). It does not allow any plastic deformation to the guidance rods, therefore this design is not recommended to testing which would obviously have high jerky movements and electrospinning process would not be continuous with high straining to the friction bearings.

On the other hand the optimized design 333 showed great result values which lowered down maximal stress in the assembly to approximately ¼ and the maximal displacement to half of previous displacement. Also the significant total mass reduction by 2,3kg compare to previous design 111 must be observed (see Tab.12). All these advantages in the proposed optimized design 333 are recommended for real life usage testing, which supposes to lead to better work ability with minimal jerky movements able to increase the velocity and acceleration of the assembly resulting in shorter working time and higher nanofiber production. Shifting of the carriage position closer to the energy chain requires minimal change in the machine design and the FEM analysis proved results of much lower loading of the whole assembly.

5.7. Modal analysis of optimized design 333

Modal analysis studies the dynamic properties or structural characteristics of mechanical structure under dynamic excitation. Furthermore explains the vibration behavior of the subassembly in reassigned eigenfrequency shapes, resonance and damping mode. The 3D CAD model was used as reference and the modal analysis were made in the mode for modal analysis in the Pro-Engineer Pro-Mechanica software. As model was taken into account the optimized design 333 (see Pic.35 and Chap.5.5) with the same loading prescription described earlier in this work as boundary conditions for FEM analysis. In this work were used the first combined 4 shapes for relevant vibration presentation which can arise in reality (see Pic.39). On the picture bellow (see Pic.39) can be seen only the combination of first four modes which predictably can occur in reality on the track of lead while movement. This shape of eigenfrequencies expresses how the subassembly vibrates and moves during the working process of electrospinning (values in Tab.13). However the frequencies reach relatively low value so the fourth mode will be the most observed one in the process.



Picture 39: Result of modal analysis in combination of first 4 modes

Particular results of each eigenfrequency values can be observed in the appendix 6 and the values of these frequencies can be seen in the table below (see Tab.13). In the combination result case was excluded the fourth mode which does not express additional construction frequency mode, but only plastic cover movement, which will not obviously happen in the welded assembly compare to the bonded model. 3D data for the modal analysis were taken as bonded model.

Table 13: Modal analysis results of design 333

Eigenfrequency Mode	Frequency [Hz]
1	25.3
2	33.6
3	42.2
4	49.5
5	52.4
6	66.5
7	87.4
8	87.9

6 DESIGN OF A NEW SPECIAL LINEAR CARRIAGE

Aim of this chapter is to design new type of carriage for the linear guiding system of current nanotechnology machine based on currently used circular linear guiding rods with plastic friction bearings (see Chap.6.1. bellow). The span of the guiding rods must be preferably kept from reasons of high voltage assembly parts preservation where all metal parts must be in distance at least 5mm/kV. Knowledge from optimization and FEM analysis of used systems was applied. Reason for new carriage design is further mass reduction with innovation and simplification resulting in better innovative application and better movement without vibrations and jerky movements.

The second intention is to propose totally new linear guidance system based on chosen supplier BAHR by the assigning company. Innovation with this linear guiding system is one piece aluminum profile resulting in easier incorporation, higher load stability, carriage velocity increase and higher trust ability of the system. Ideas for the machine working space must be proposed (see Chap.6.2. bellow).

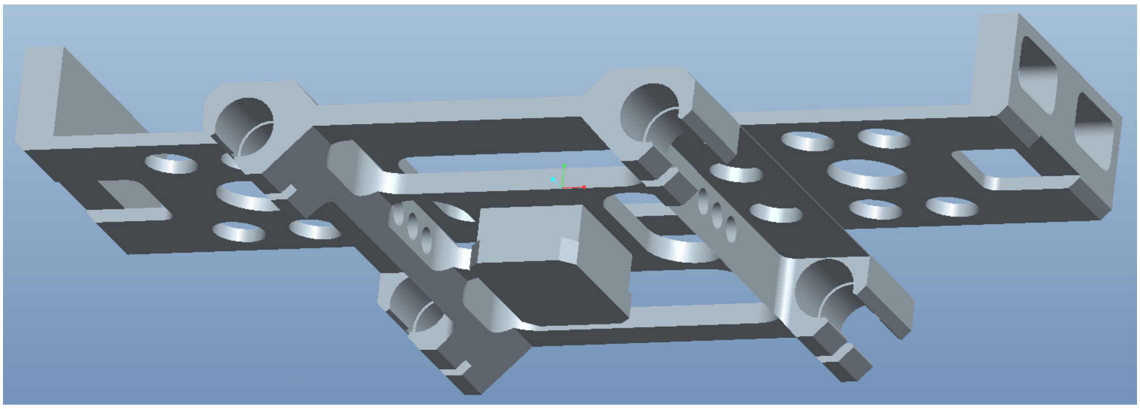
6.1. Design based on current guidance system

One minor change was proposed with the optimized 333 carriage design incorporating also the base plate dimension optimization along with the side parts material and dimension keeping. As the second option totally new carriage concept was proposed as one piece aluminum alloy machined part.

6.1.1. Optimized 333 carriage design with changed base plate

At first the design 333 was optimized for the most reliable mass and strain dispersion in the assembly. Where five holes was added in body of the carriage in the middle for improving the malleability and the base plate was optimized. Thickness of this plate was reduced by 3mm and old reliefs were removed due to the causing higher strains in the assembly (for comparison see Pic.8).

Furthermore the holed reliefs were proposed out of the edge with the carriage light weighting whole design. These design (see Pic.40) properties are summarized below and are result of innovative knowledge of FEM analysis applied into the design change along with the fact that the carriage is part of the whole assembly together with the nanotechnological head but focus was on carriage design.

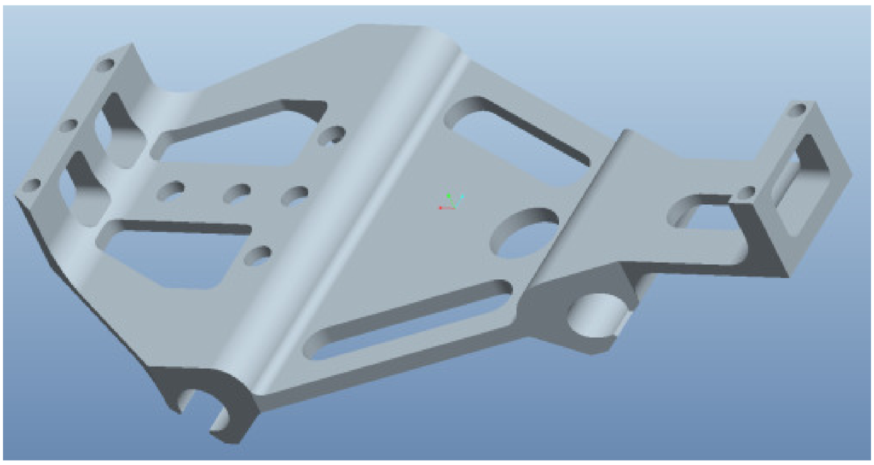


Picture 40: Proposed 333 optimized carriage design

- VOLUME = 5.19e+05 MM^3
- SURFACE AREA = 1.97e+05 MM^2
- AVERAGE DENSITY = 3.16e-06 KILOGRAM / MM^3
- MASS = 1.64e+00 KILOGRAM

6.1.2. New carriage design proposal with three frictional bearings supply

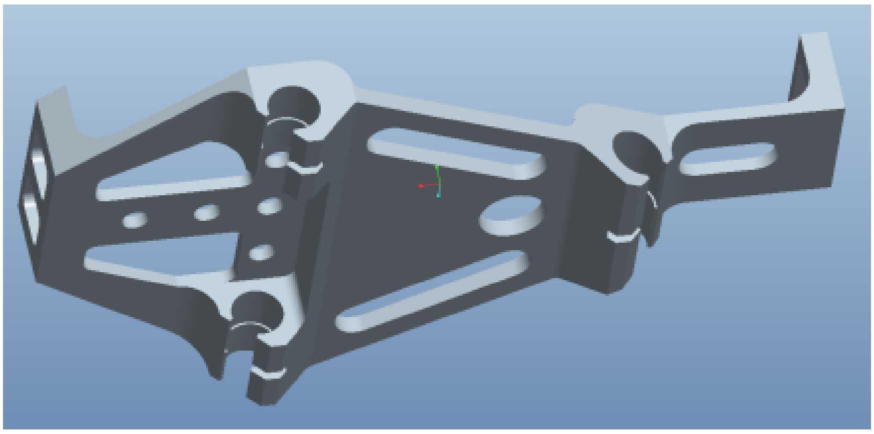
Completely new design is coming from the idea that the previous carriage desings are statically over determined and actually one of the resons why are occuring the jerky movements to the guidance rods along with the ideal COG optimization for the belt drive.



Picture 41: Proposed new carriage design - top view

Therefore the new design is proposed with three frictional bearings along with keeping the distance again of the rods resulting in minimal change of the machine design change (see Pic.41). It is proposed that the whole carriage will be machined from one block of material resulting in decrease of part amount, installation acceleration and drastically reduce jerky movements of the whole assembly with the lowest die displacement. These assumptions are critical for the best movement option and were intention for this design change.

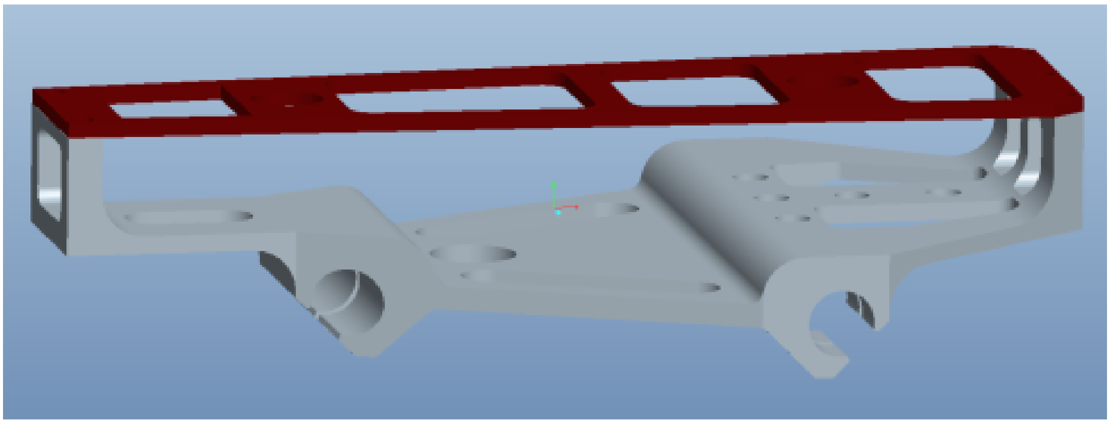
Reliefs for mass reduction were designed according to lowest possible stress achievement as well as sharp edges were eliminated which cause the highest strains and critical places in the assembly while loading according to the previous experience and FEM proceeded analysis.



Picture 42: Proposed new carriage design - bottom view

- VOLUME = 4.17e+05 MM^3
- SURFACE AREA = 1.20e+05 MM^2
- DENSITY = 2.71e-06 KILOGRAM / MM^3
- MASS = 1.13e+00 KILOGRAM

The nanotechnological head will be connected in the same way like in the design 333 with the different of the base carriage which is designed in this case to be sturdy especially at the right side closer to the energy chain connection due to the higher mass concentration and increased loading to this side. COG of the whole assembly must be of course below the belt drive connection. It is proposed that the nanotechnological head key connection will be spread wider compare to the previous design on the top plate again resulting into the higher stability and reducing the critical displacement of the dies on that. Top plate supposes to be fastened with the carriage by the 5 counter bolts from the top side.



Picture 43: Proposed new carriage design with top plate

This elegant design proposal is not optimized for the serial production on the milling machine from the technological point of view although for higher speed proposal, mass reduction, jerky movements elimination and installation process or maintenance improvement yes.

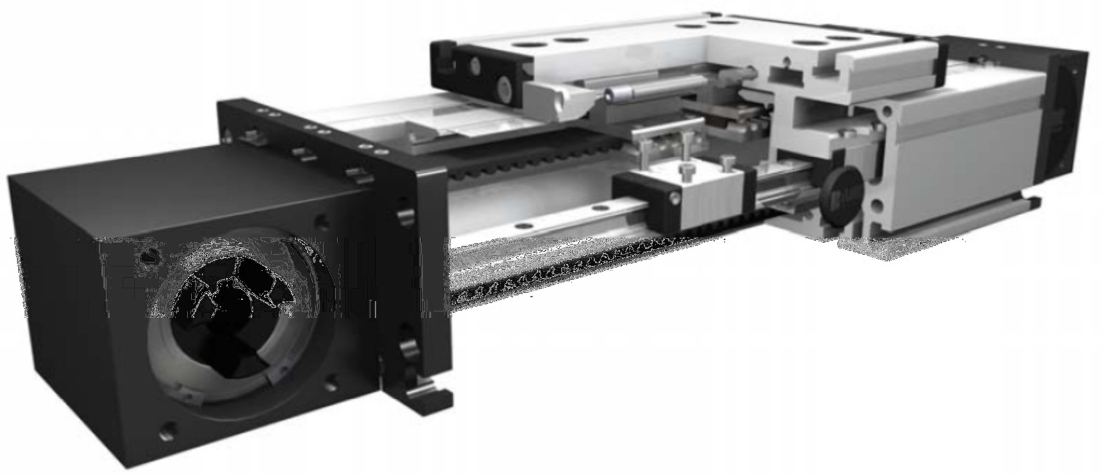
6.1.3. Evaluation of the new design proposals

Design based on current 333 carriage design was proposed since it is the first step for testing phase of the new linear guidance age in this nanotechnology machine and it led to the mass reduction from 2,44kg (see Pic.8) to 1,64kg of optimized 333 design (see Pic.40). However new proposed carriage design expresses further mass reduction possibility up to 1,13kg meaning that these optimizations carry other 2,44 – 1,13 = 1,31kg mass savings with reliable strains. Along with the fact of part amount reduction and minimalizing the use of the bolt connection in the carriage up to two machined parts from aluminum alloy.

Furthermore must be mentioned that the new proposed design is not technologically optimized for the production and the future suggestion would be in higher production scale of these carriages have casted semi-finished product in order to decrease the price and improve the production process of finishing operations.

6.2. Linear guidance system from company Bahr

The unit from company Bahr consists of a rectangular aluminum profile with two integrated rail guides. The carriage is moved by a belt drive. Each standard pulley has got one coupling claw on one side. Belt tension can be readjusted by a simple screw adjustment device in the carriage. This device can also be used for symmetrical adjustment of two or more linear units running parallel. The openings of the guide body are sealed with three stainless steel cover bands to protect the guide from splash water and dust as well as it is chemically resistant in usage of electrospinning nanotechnology. Alternatively, the opening can also be covered with a bellow or can be delivered without cover bands. However in current design would be better with stainless steel covers (see Pic.44).



Picture 44: Profile linear guidance system DSZ from company BAHR [17]

Fitting position: As required. Max. length 6.000 mm without joints.

Travel speed: Max. 6 m/s

Carriage mounting: By T-slots.

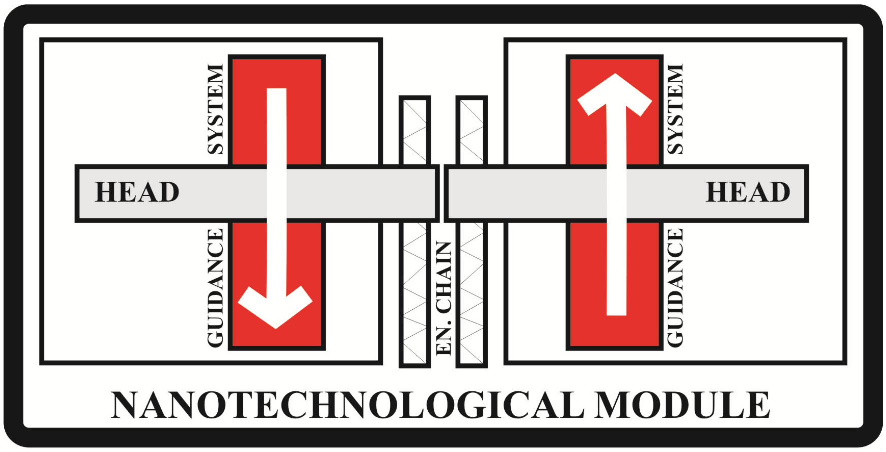
Unit mounting: By T-slots and mounting sets. The linear axis can be combined with any T-slot profile.

Belt type: HTD with steel reinforcement, no backlash when changing direction, repeatability ± 0,1 mm.

Carriage support: In the standard version, the carriage runs on 4 runner blocks which can be serviced at a central servicing position. The number of runner blocks can be also increased if needed. [17]

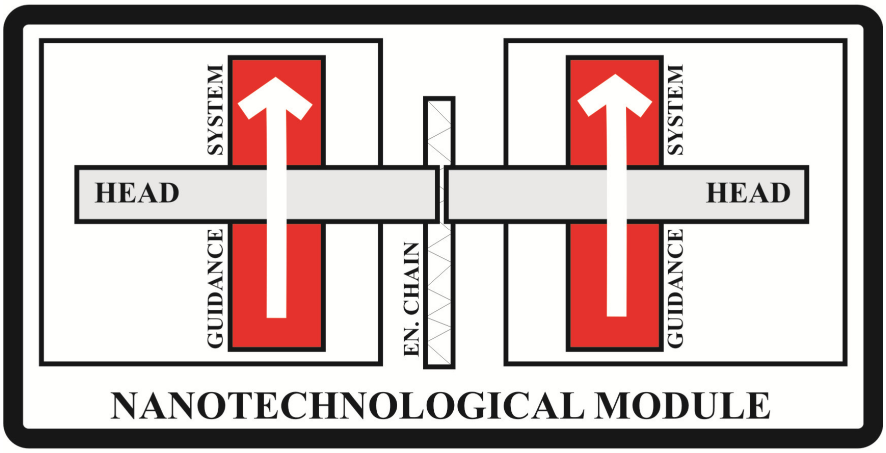
This guidance system have been chosen from catalog of Bahr company for a reason of better stability of the whole functioning system as well as diminishing the troubles with assembling and maintenance of the system in the company, stainless steel sealing and control ability of the linear carriage in nanofibering process. This assembly can be easily included in current nanotechnology machine design and substitute current problematic mounted system on aluminum profiles. Proposals for innovative nanotechnology module working space are described below (see Pic.45 - 49). The outside dimensions of the machine would stay the same which is called nanotechnological module, but the nanofibering process would be led differently. Electrospinning is complicated process not fully described in this work, but these innovation ideas can be tested and evaluated for higher production rate.

Currently are in the machine two linear guidance units running continuously opposite each other which are taking a lot of extension space bellow the working space (see Pic.45). Consequently the high voltage and the nanofibering process are restricted by the speed of their movement. There are also troubles with creating eddy whirls influencing the Taylor cones creation by the dynamic assembly movement.



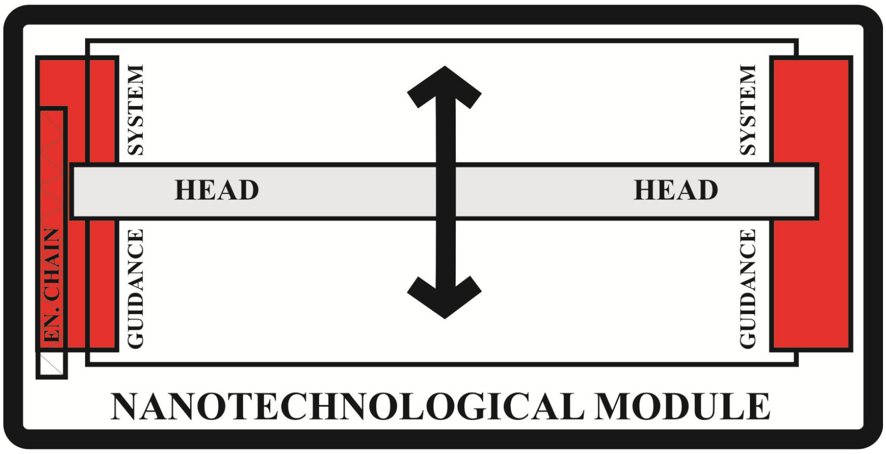
Picture 45: Current nanotechnological module design

New overview can be taken into account when the design has been optimized and can freely move faster. Therefore proposition is also to move the carriages in the same direction but faster (see Pic.46). Consequently higher nanofiber production will be created as well as eddy whirls by the dynamic movement will be decreased, working space increased and one energy chain removed.



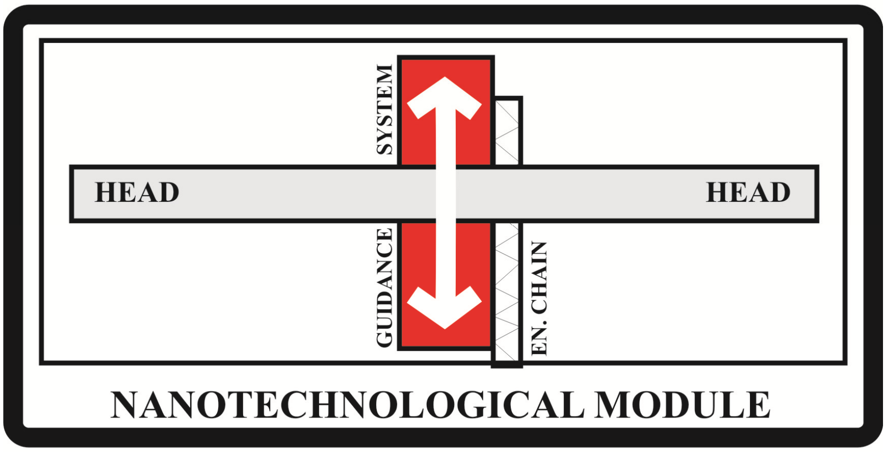
Picture 46: Simultaneous nanotechnological proposal

Other new concept can use the guiding systems described in the chapter 3 (see Tab.4), where especially the self-aligning system could be applied (see Pic.6). Simple roll guidance would be moved to the sites of the nanotechnological module where in between the new long nanotechnological head is transferred (see Pic.47). Head can move faster in this case and the nanofiber production would be increased with higher stiffness and simplicity of the system. The built-up space in the working area would decrease and so the development cost would lower down.



Picture 47: Reorganized guiding system with bigger head

According to the proposed linear guiding system from company Bahr (see Pic.44) one guidance system can be used as higher stability guiding system to which only one head could fulfill the whole working space of the nanotechnological module (see Pic.48). This solution would radically decrease the cost of the functional module and increase the nanofiber production as well as it takes into account the option of faster one direction moving head in one working module completely filling up the working area (see Pic.48).



Picture 48: One guidance system module proposal

Guiding system from company Bahr can be also used in the option of continuously running opposite each other two systems (see Pic.45) as well as in simultaneous two running guidance systems (see Pic.46). In these cases the Bahr guidance system would only replace current friction guiding systems. The stability and simplicity would be increased but the cost of the module would not be lowered down presumably. These proposals must be furthermore economically researched and their application incorporated into the machine module body.

7 CONCLUSION

Content of this diploma thesis was to optimize the shape of the carriage used in nanotechnology mass production machines Nano Spider with regard for its weight reduction and values of the maximal stress deformation as well as new linear guidance system proposal research. Due to the design construction change of this apparatus was taken in consideration the design and dimensions of current carriage and nanotechnology head for polymeric fluid application used as well as the spacing of current linear guide rails in the machine and energy chain connection was kept. This proposal was accomplished and was leading to the minimal design change in the machine module embodiment. Consequently due to theoretical prerequisites the weight decrease was achieved from original 11,3kg to 9,1kg. Kinematic calculations of the belt drive and loading forces were carried on and minimal and maximal actuating mechanism for tested velocity and acceleration profiles were completed.

Furthermore the optimal deformation of the carriage was accomplished with respect to the given places of dies spacing for polymer application on the wire electrodes for electrospinning process. Die displacement in the worst scenario was reduced to the half of the previous one to 0.26mm. In these places displaced contact of the passage on the head and the electrode was minimized during the application. By the optimized shape of the proposed carriage design was completed modal analysis from reason of assembly eigenfrequencies detection. Knowledge of these eigenfrequency values will be further employed during the optimization velocity profile of the carriage movement, where its calculation was also described in this work. Optimized design 333 showed great result values which lowered down maximal stress in the assembly to approximately ¼ and the maximal displacement to half of previously used designs. Also distinguished total mass reduction by 2,2kg compare to previous design 111 must be significantly observed.

All these advantages in the proposed optimized design 333 are recommended for real life usage testing, which supposes to lead to better work ability with minimal jerky movements able to increase the velocity and acceleration of the assembly resulting in shorter working time and higher nanofiber production. Shifting of the carriage position closer to the energy chain requires minimal change in the machine design and carried

FEM analysis proved results of much lower loading of the whole assembly. However in real testing mode was till this time tested the design 333 up to the change when the counter weight was not removed yet. There does not supposed to be any other impact with continuing of proposed model optimization and real life testing in the machine up to the point when the carriage has to be moved due to the COG optimization.

New carriage design was further developed with consideration of continuous mass reduction equal to other negative -1,3kg, conditioning innovation and simplification resulting in better innovative application and better movement without vibrations and jerky movements with already optimized center of gravity of the whole assembly. Along with the fact of part amount reduction and minimalizing the use of the bolt connection in the carriage up to two machined parts from aluminum alloy. However this design was not optimized in this work from the technological point of view for one-shot production and its economical difference compare to previous designs.

Further research suggestions:

For further research is recommended to continue proposed plan for current design change described in this work. As well as testing of new designed carriage with current nanotechnological head, which will allow proceed faster and better electrospinning process resulting into nanofiber production increase overall. Furthermore the research on the nanotechnological head can be carried on leading also to other mass reduction still with the same staining. Continuation is in profile guidance system described as BAHR or other being researched along with the quality of the electrospinning process in the module for different approach to the direction of movement. These profile guidance systems can be also incorporated into the lab equipment being produced by the company allowing testing these systems in smaller production scale and approving the concept for new age of Nano Spider machines.

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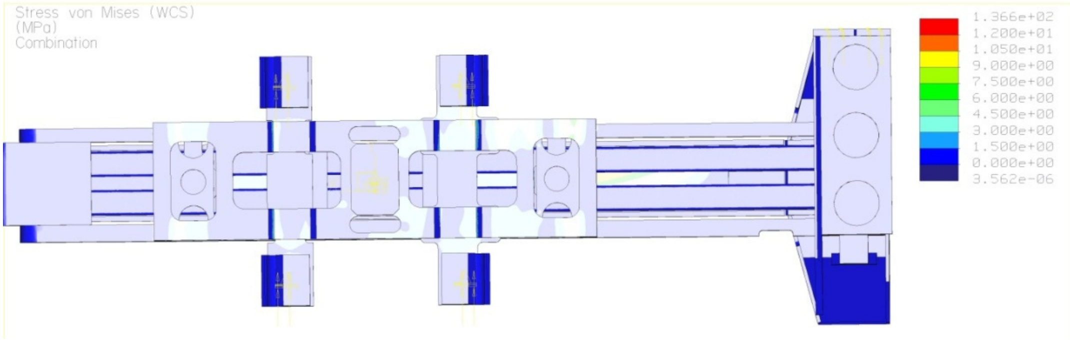
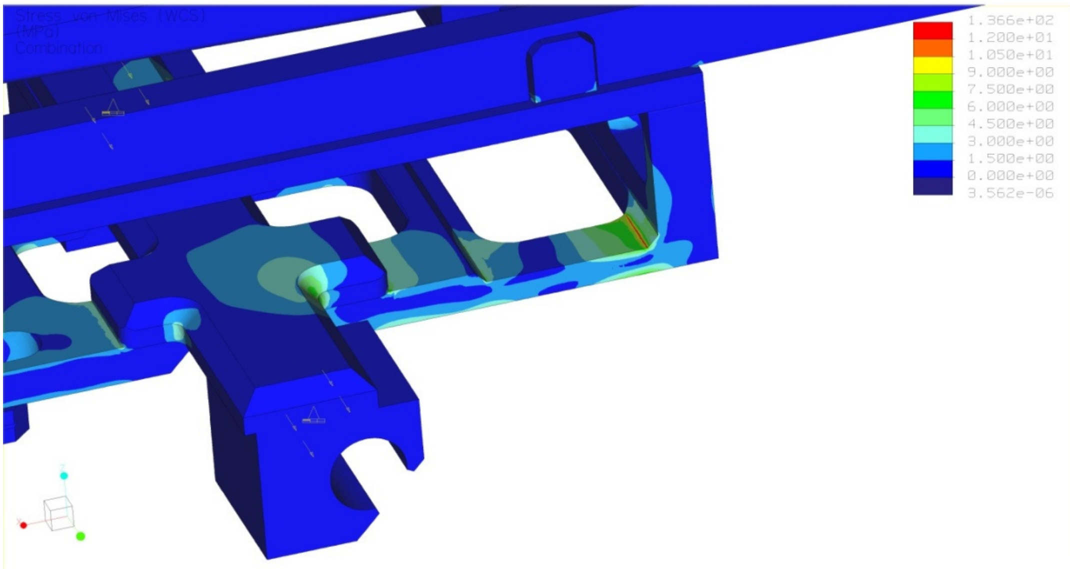
APPENDIXES

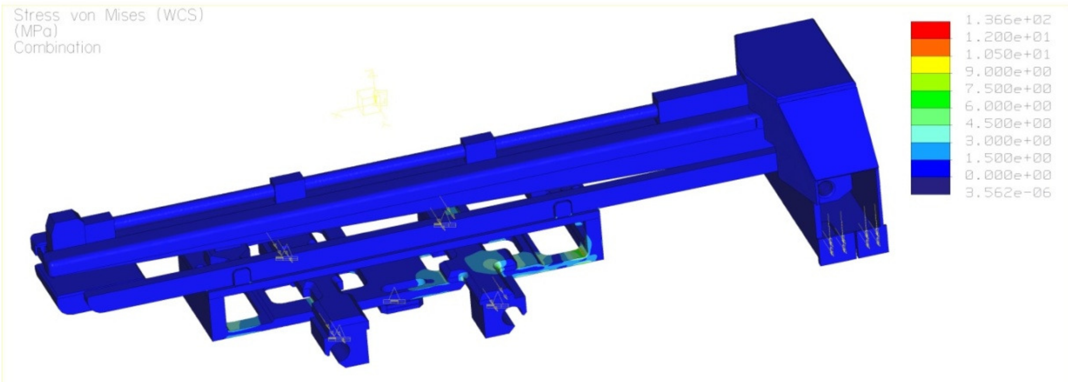
Hereby follows additional supplements for this diploma thesis closely adding information and detailed descriptions for carriage and head assembly designs as well as data sheet for Bahr guidance system and search of linear guidance systems.

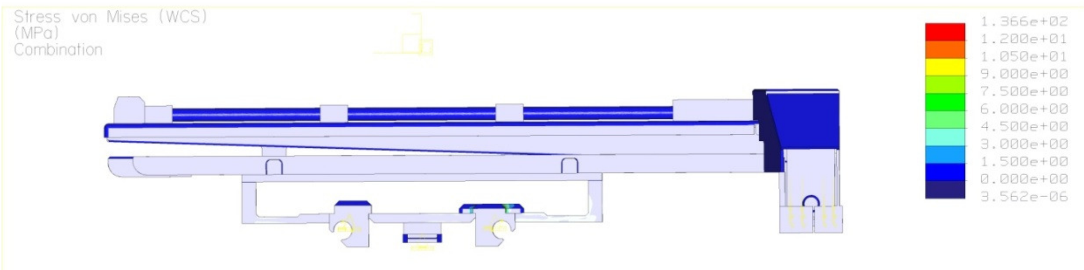
List of appendixes

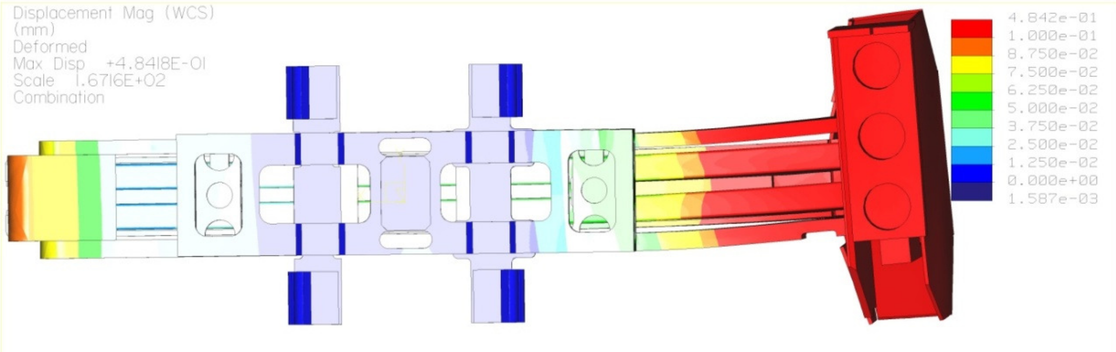
Appendix 1: FEM Analysis of design 111







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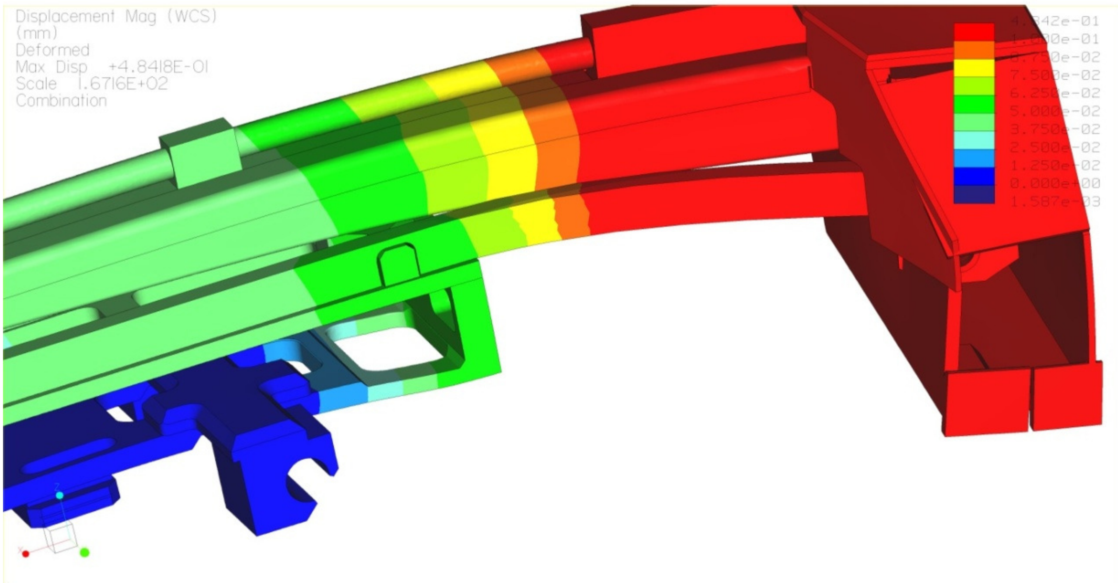
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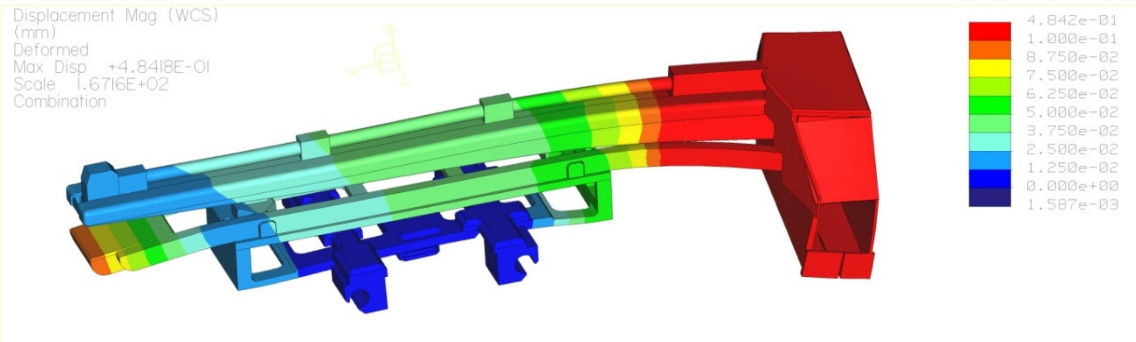
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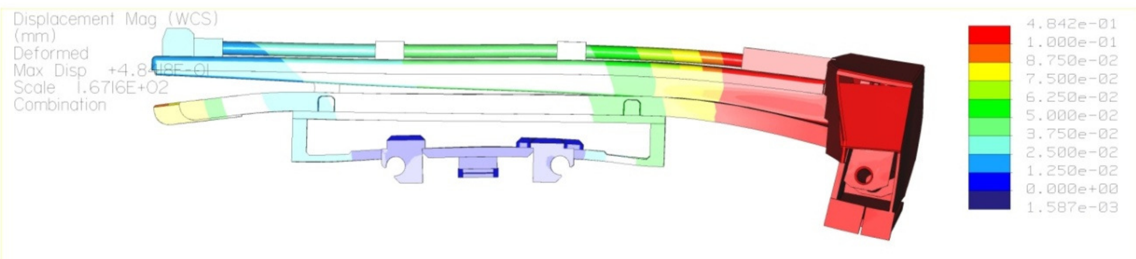
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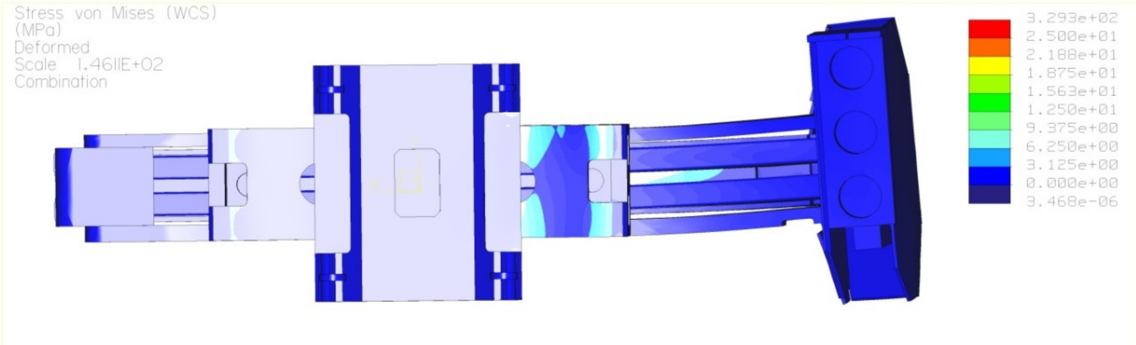
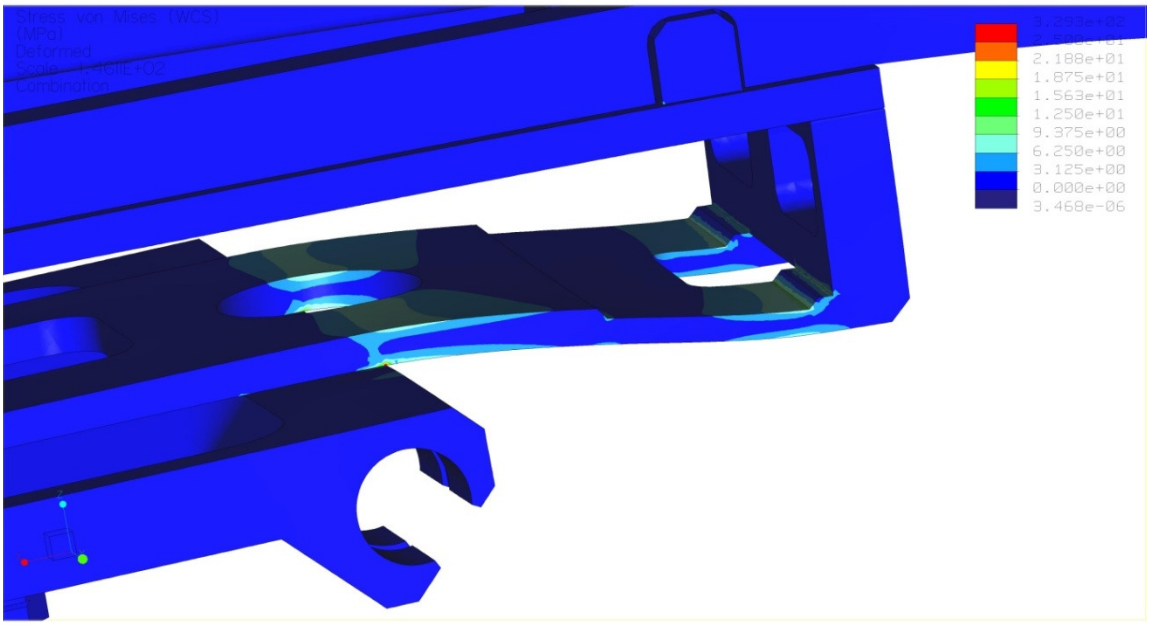
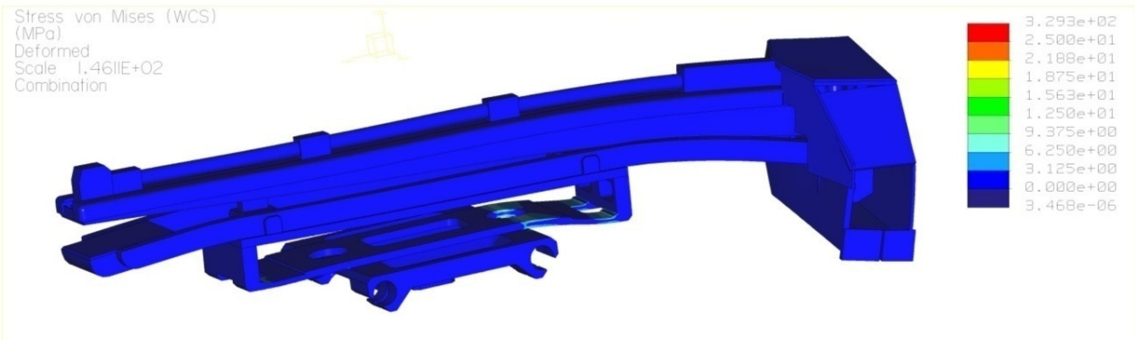
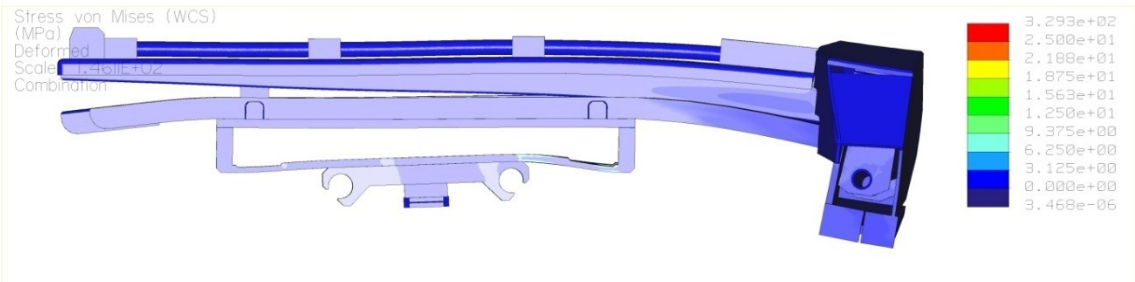
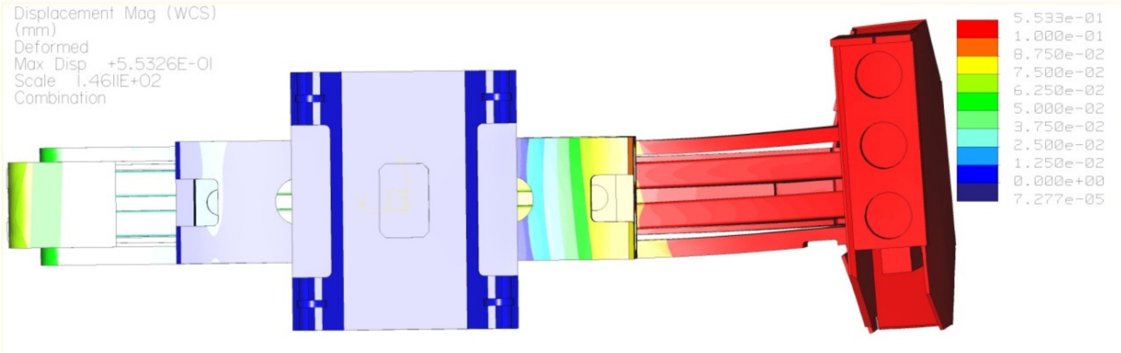
Appendix 2: FEM Analysis of design 222







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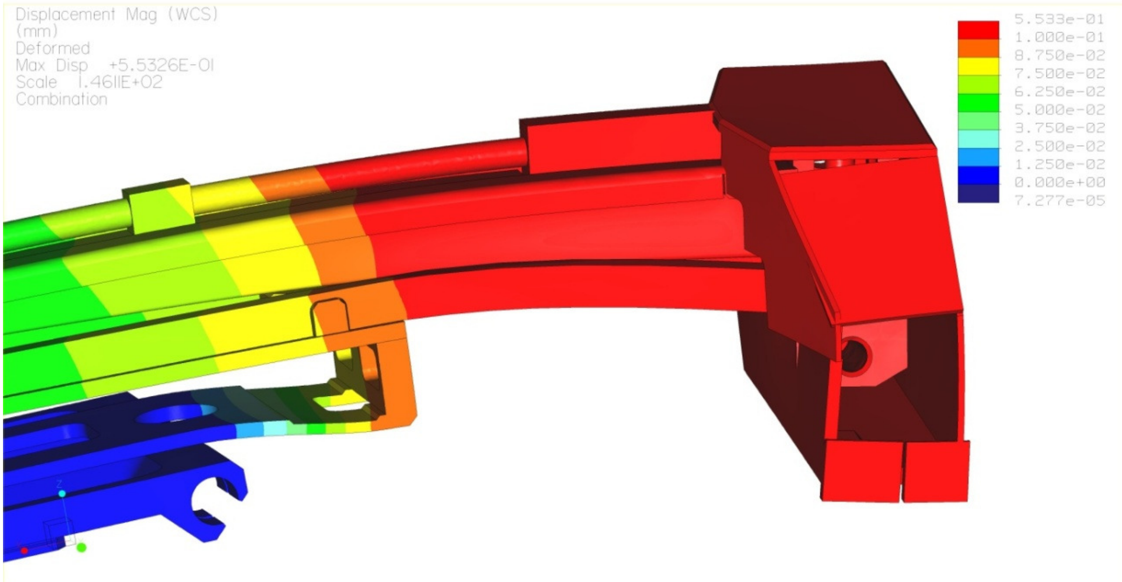
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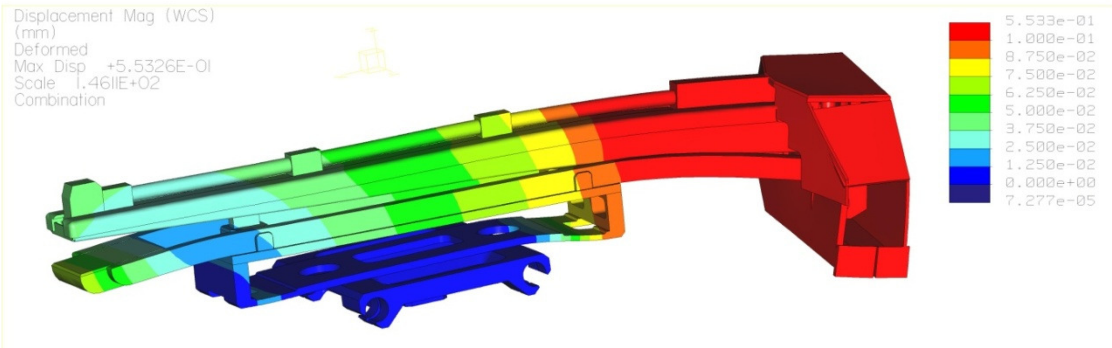
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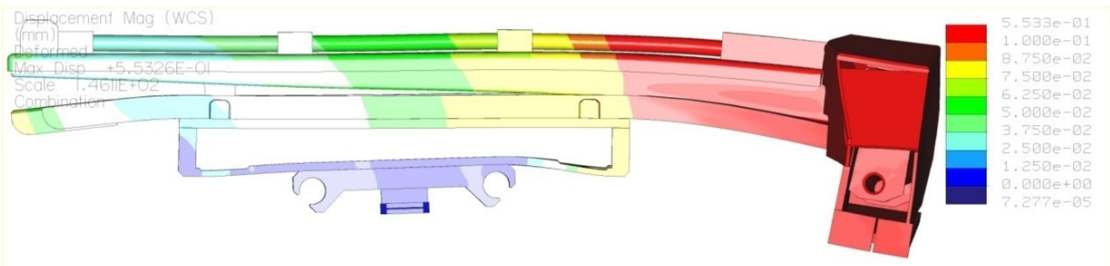
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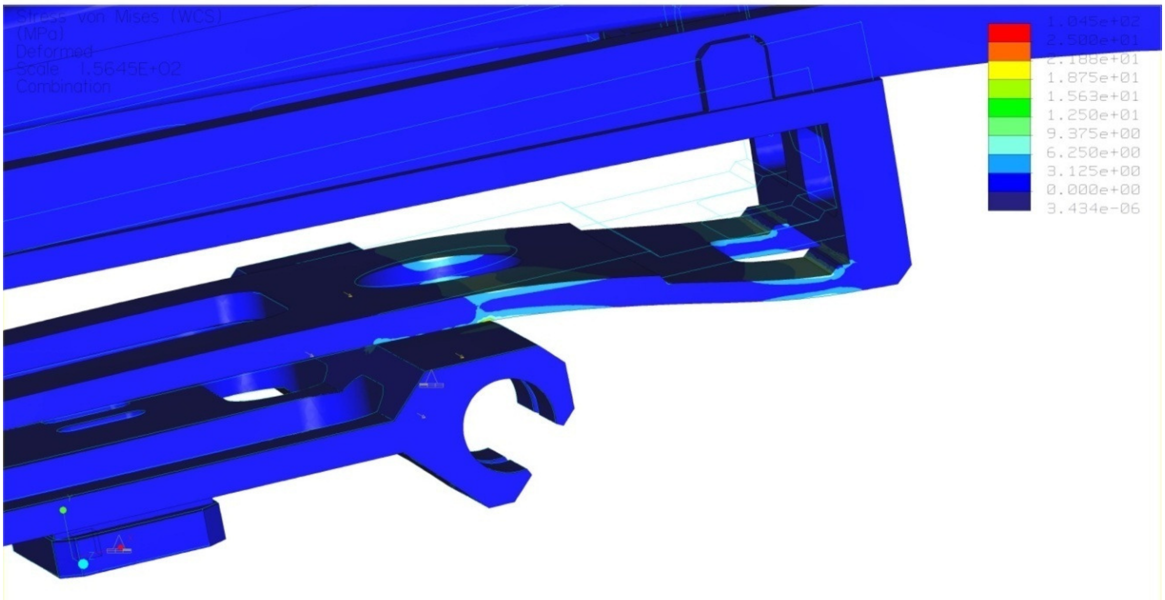
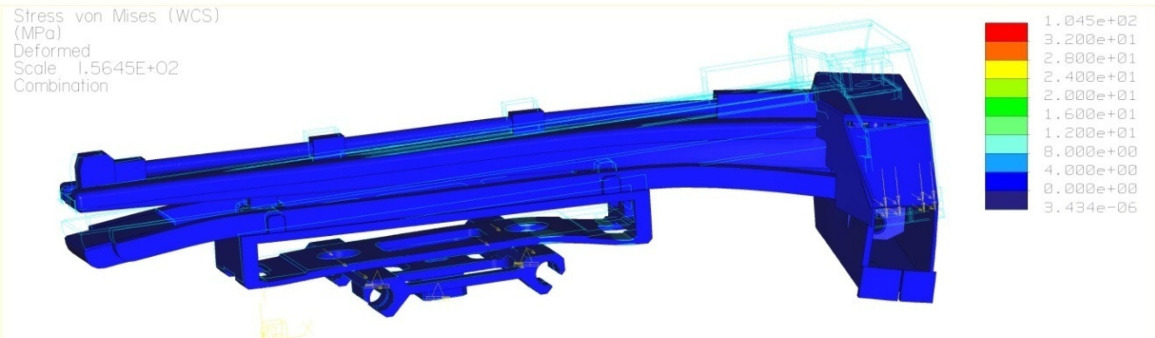
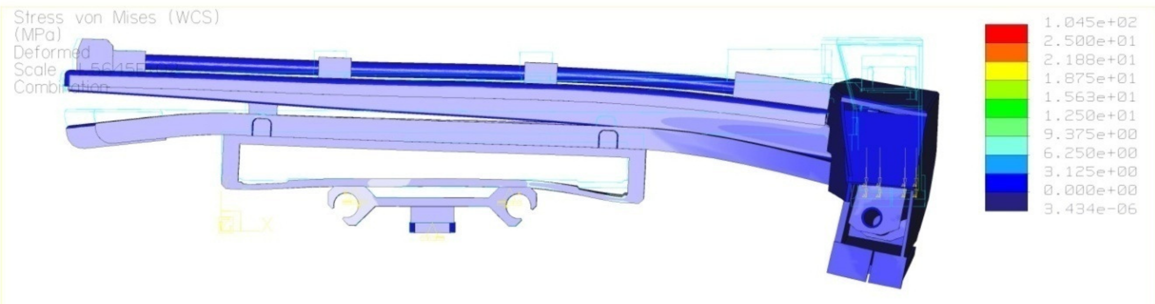
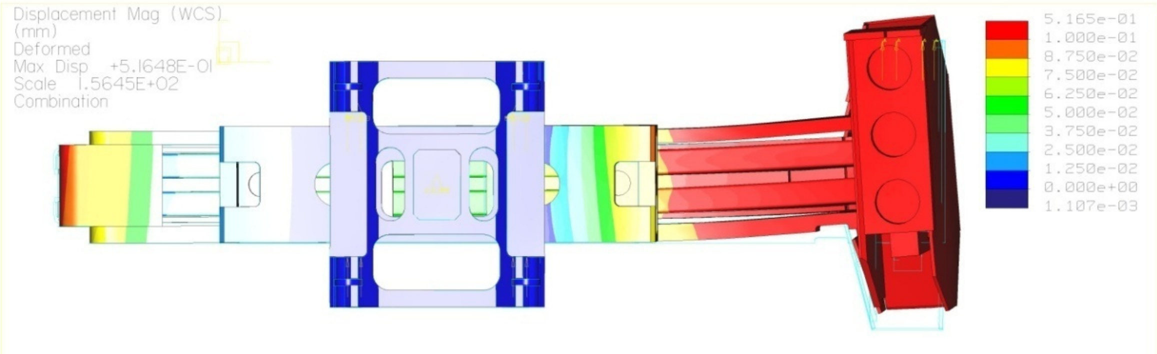
Appendix 3: FEM Analysis of design 333 – original





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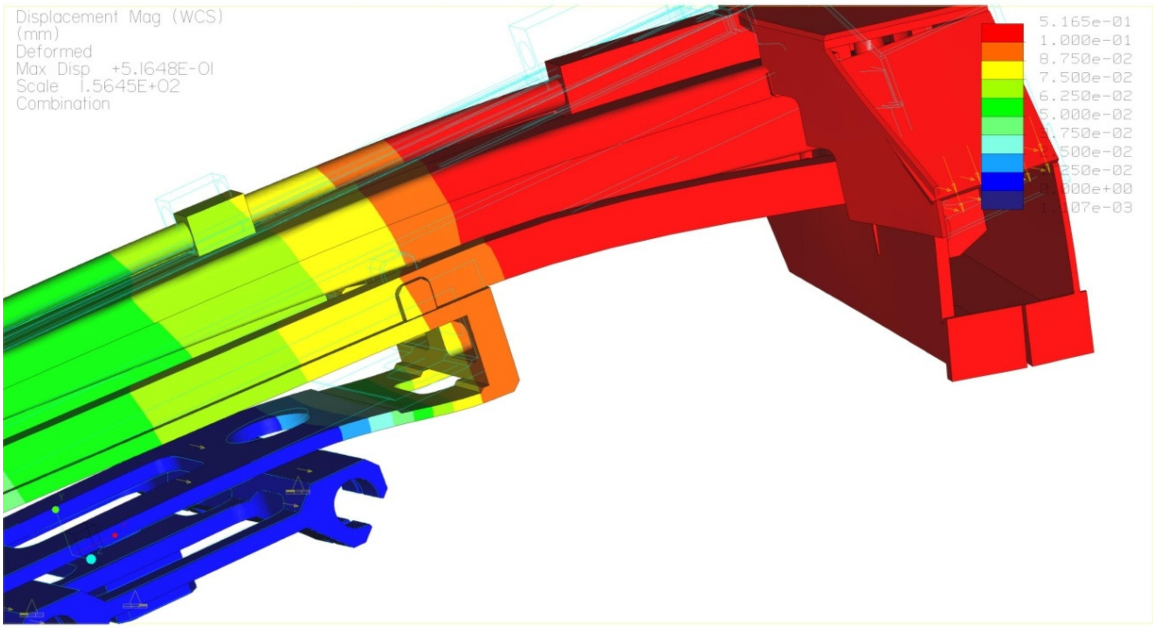
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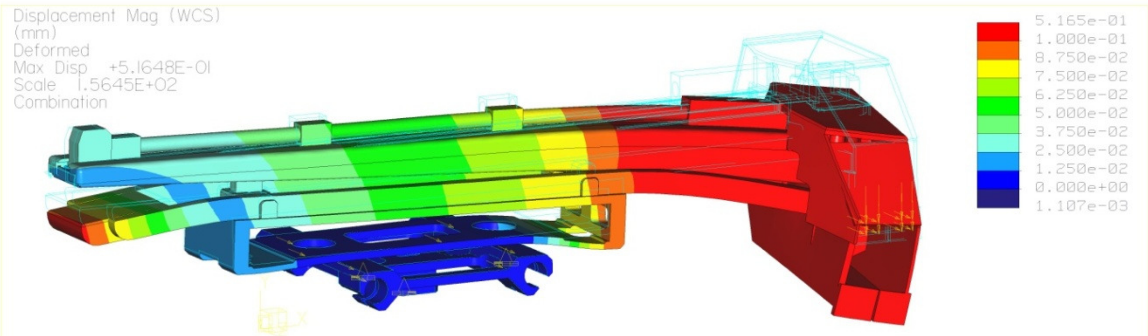
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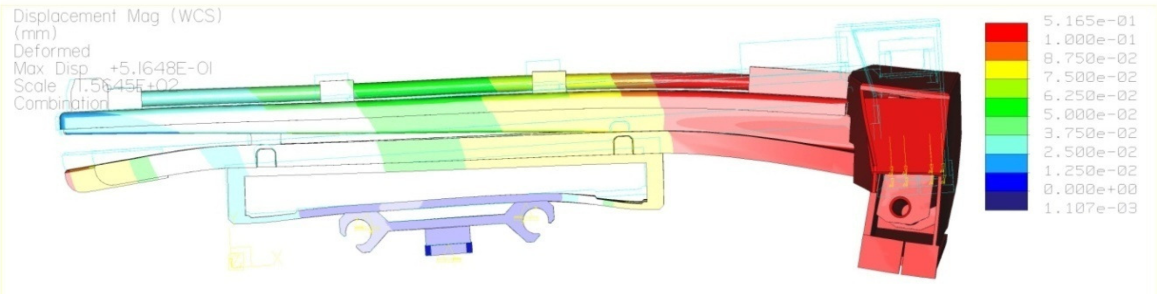
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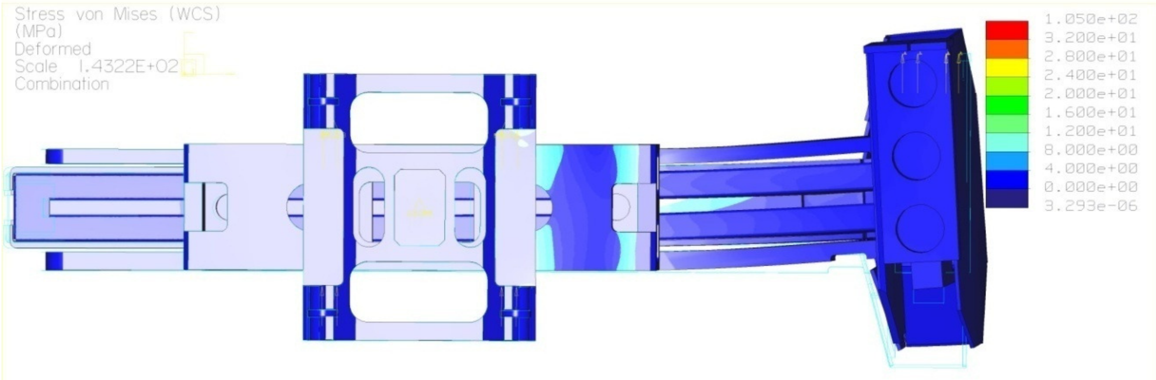
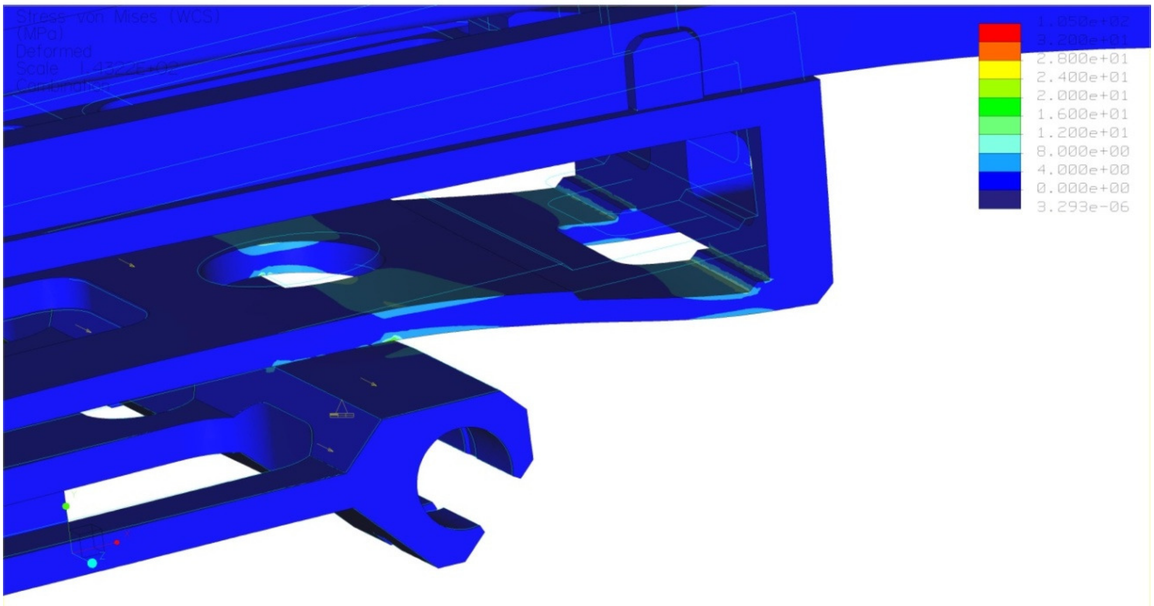
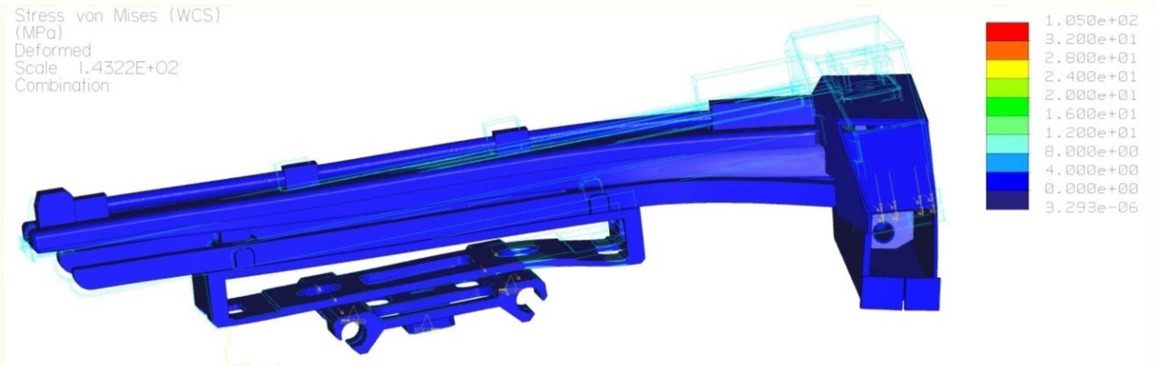
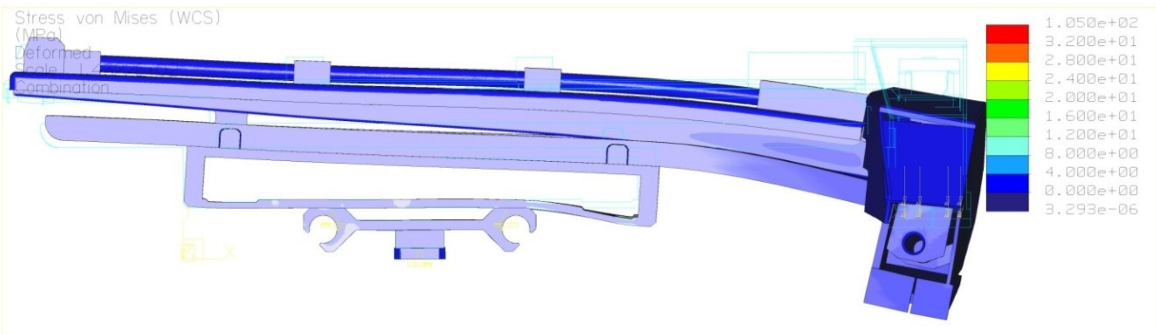
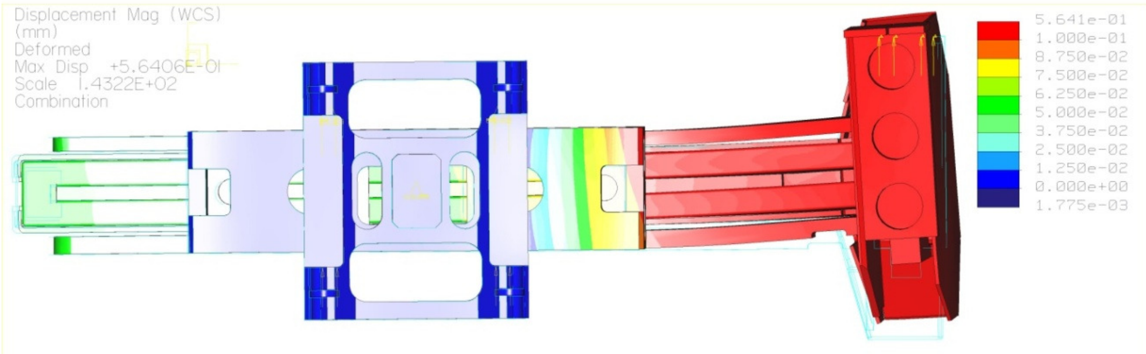
Appendix 4: FEM Analysis of design 333 – without counter weight

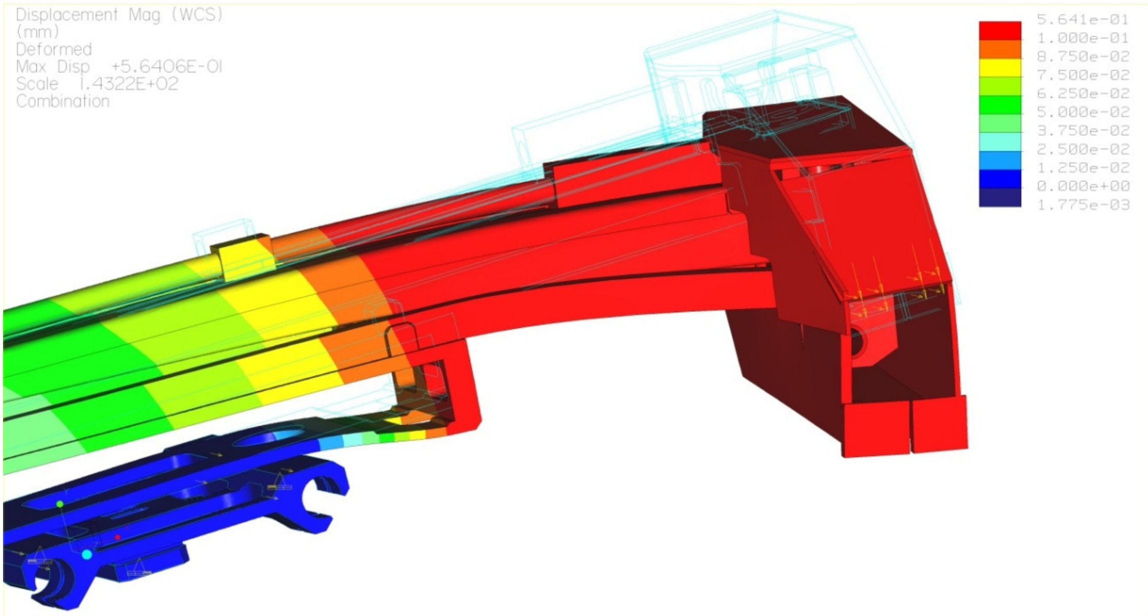


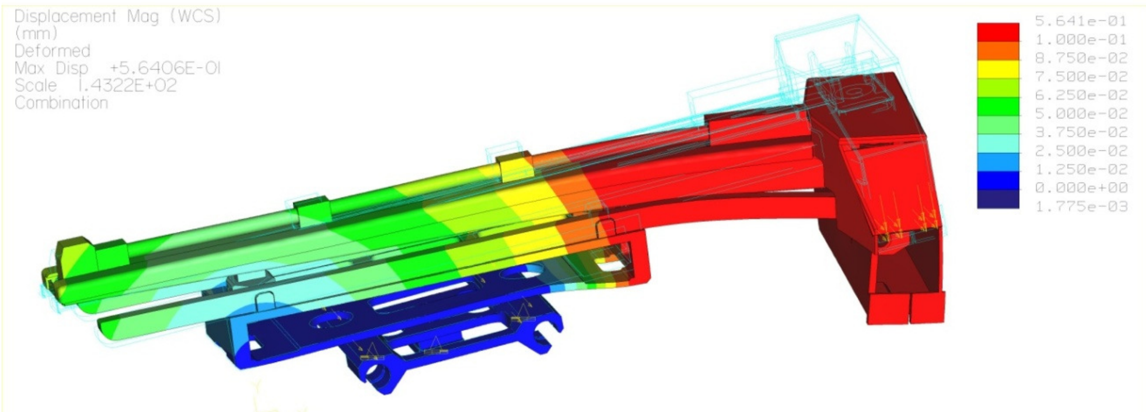


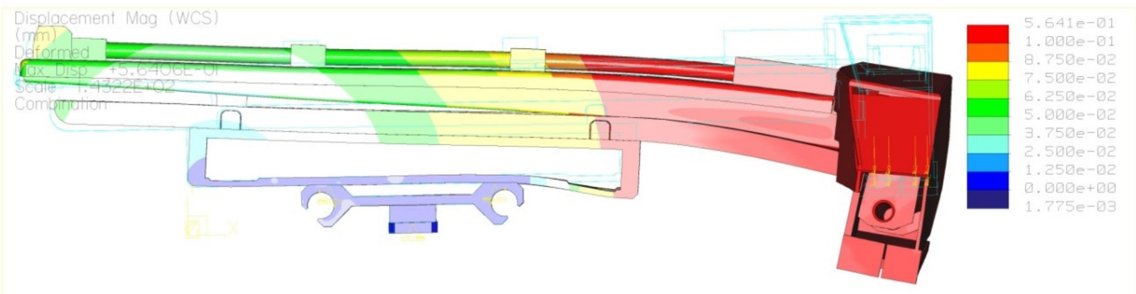




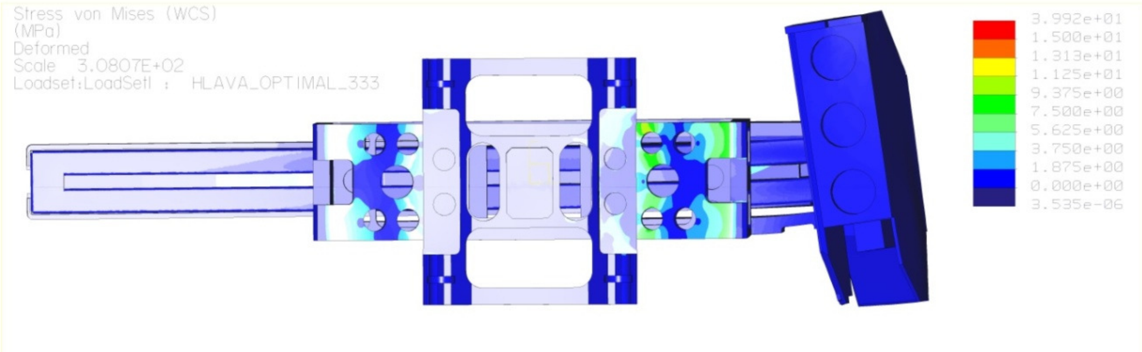

Displacement Mag (WCS)
(mm)
Deformed
Max Disp +5.6406E-01
Scale 1.4322E+02
Combination
5.641e-01
1.000e-01
8.750e-02
7.500e-02
6.250e-02
5.000e-02
3.750e-02
2.500e-02
1.250e-02
0.000e+00
1.775e-03

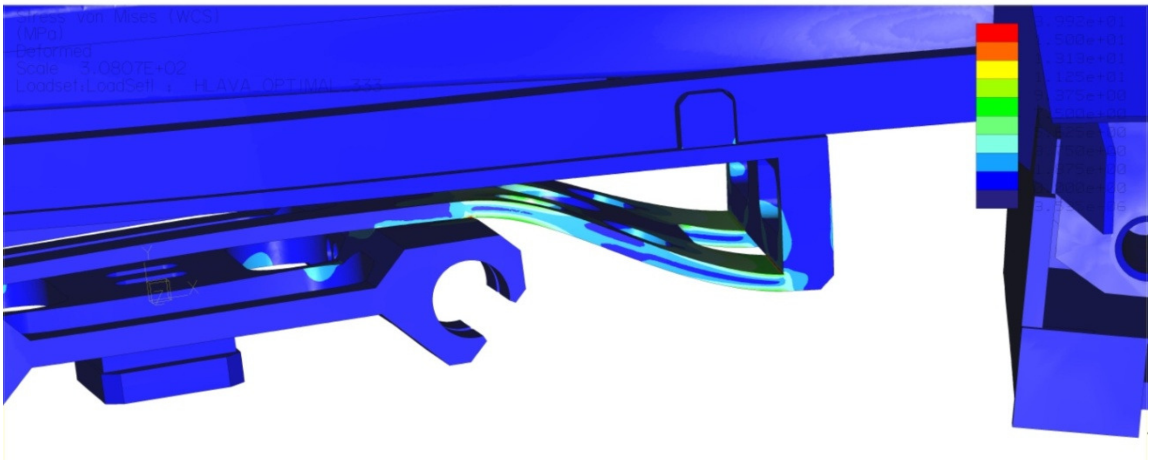

Displacement Mag (WCS)
(mm)
Deformed
Max Disp +5.6406E-01
Scale 1.4322E+02
Combination
5.641e-01
1.000e-01
8.750e-02
7.500e-02
6.250e-02
5.000e-02
3.750e-02
2.500e-02
1.250e-02
0.000e+00
1.775e-03

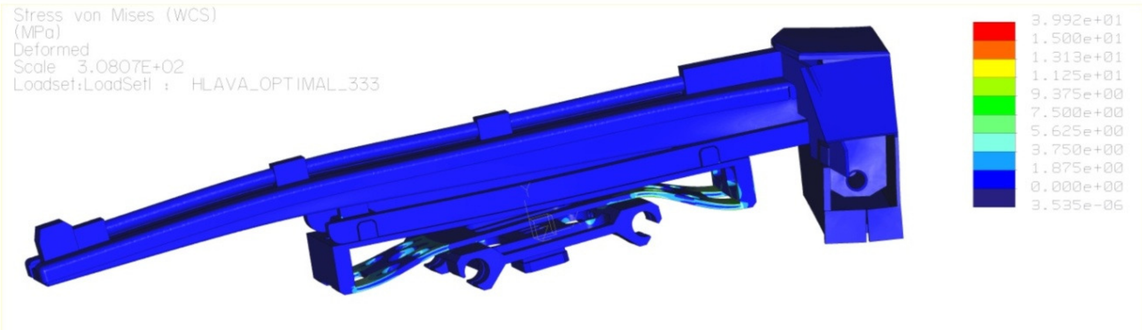

Displacement Mag (WCS)
(mm)
Deformed
Max Disp +5.6406E-01
Scale 1.4322E+02
Combination
5.641e-01
1.000e-01
8.750e-02
7.500e-02
6.250e-02
5.000e-02
3.750e-02
2.500e-02
1.250e-02
0.000e+00
1.775e-03

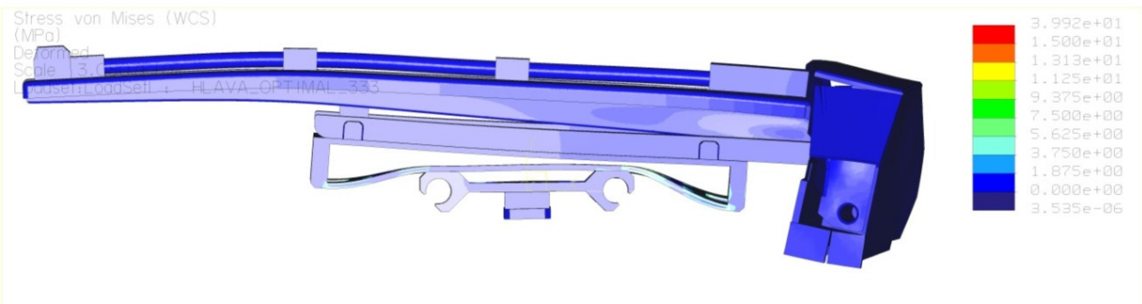

Displacement Mag (WCS)
(mm)
Deformed
Max Disp +5.6406E-01
Scale 1.4322E+02
Combination
5.641e-01
1.000e-01
8.750e-02
7.500e-02
6.250e-02
5.000e-02
3.750e-02
2.500e-02
1.250e-02
0.000e+00
1.775e-03

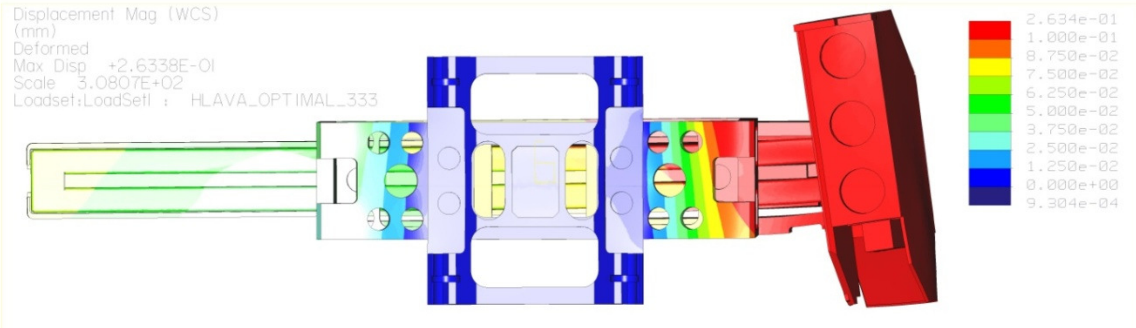
Appendix 5: FEM Analysis of design 333 – optimal










Displacement Mag (WCS)
(mm)
Deformed
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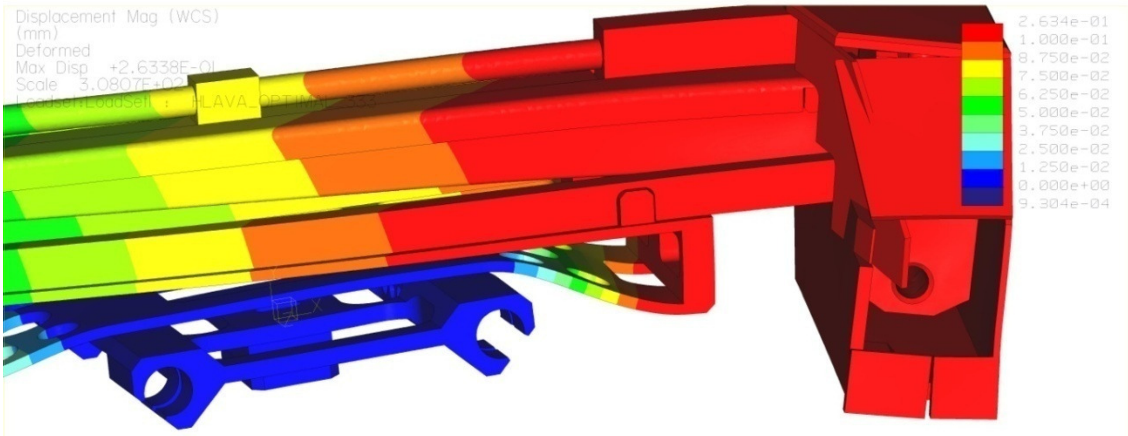
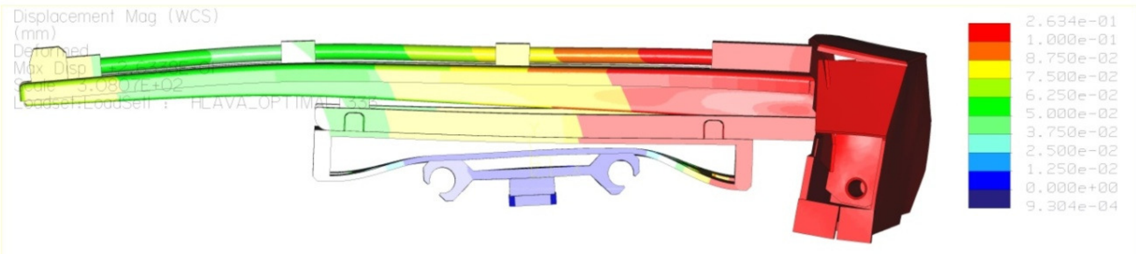
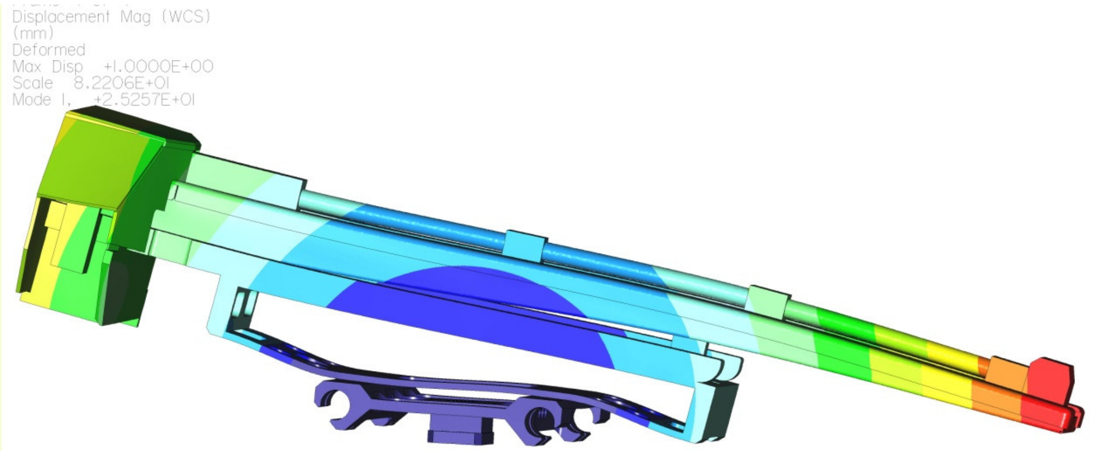
Scale 3.0807E+02
Loadset:LoadSet1 : HLAVA_OPTIMAL_333
2.634e-01
1.000e-01
8.750e-02
7.500e-02
6.250e-02
5.000e-02
3.750e-02
2.500e-02
1.250e-02
0.000e+00
9.304e-04

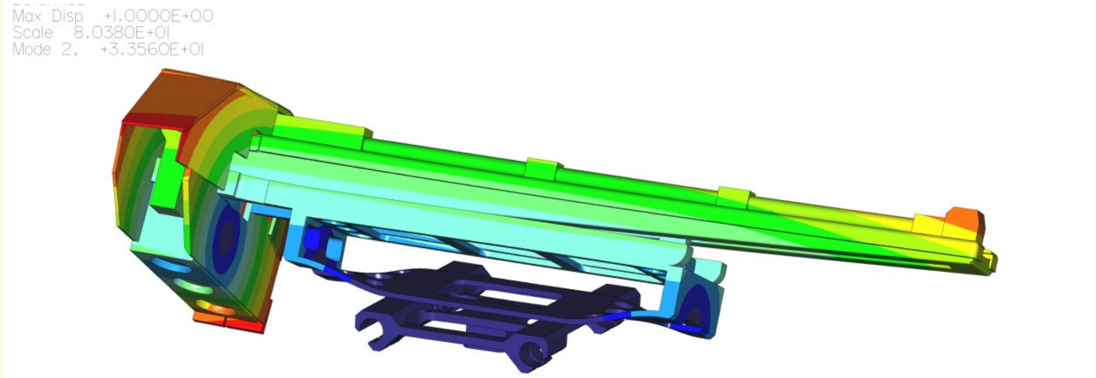

Displacement Mag (WCS)
(mm)
Deformed
Max Disp +2.6338E-01
Scale 3.0807E+02
2.634e-01
1.000e-01
8.750e-02
7.500e-02
6.250e-02
5.000e-02
3.750e-02
2.500e-02
1.250e-02
0.000e+00
9.304e-04

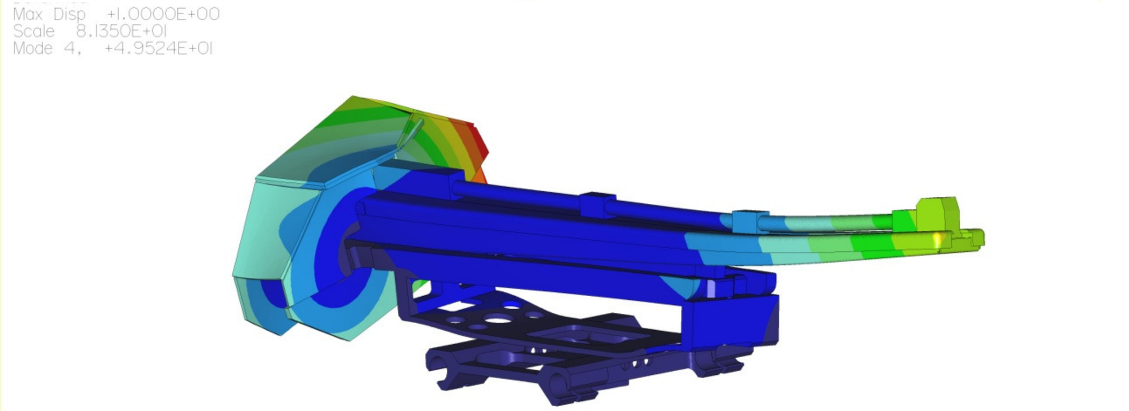

Displacement Mag (WCS)
(mm)
Deformed
Max Disp +2.6338E-01
Scale 3.0807E+02
2.634e-01
1.000e-01
8.750e-02
7.500e-02
6.250e-02
5.000e-02
3.750e-02
2.500e-02
1.250e-02
0.000e+00
9.304e-04

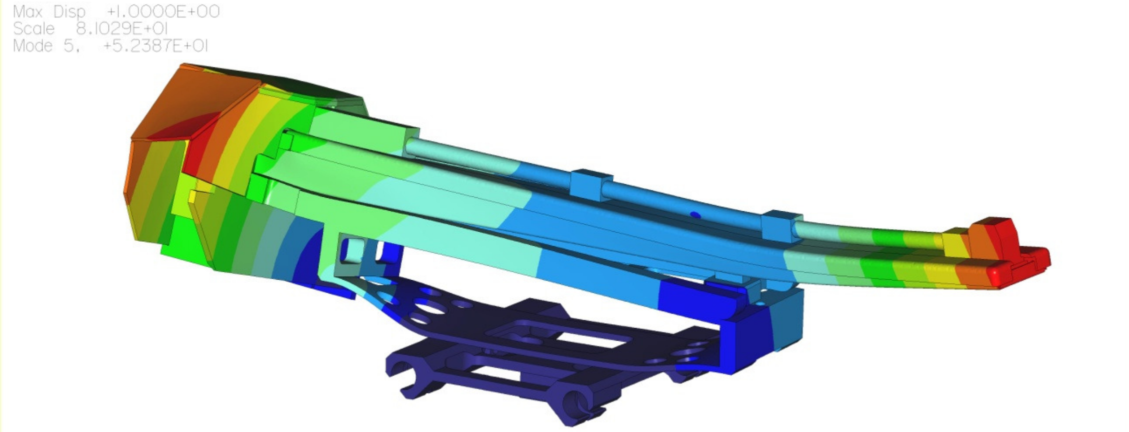

Displacement Mag (WCS)
(mm)
2.634e-01
1.000e-01
8.750e-02
7.500e-02
6.250e-02
5.000e-02
3.750e-02
2.500e-02
1.250e-02
0.000e+00
9.304e-04

Appendix 6: Modal analysis of optimized design 333 (4x shapes)









Appendix 7: Specification of Bahr DSZ guidance system

Positioning system DSZ 120, 160, 200

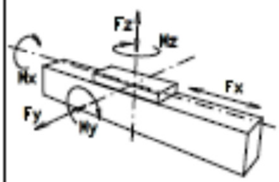
Specifications

Belt drive

Function:
This unit consists of a rectangular aluminium profile with 2 integrated rail guidess. The carriage is moved by a belt drive. Each standard pulley has got one coupling claw on one side. Belt tension can be readjusted by a simple screw adjustment device in the carriage. This device can also be used for symmetrical adjustment of two or more linear units running parallel. The openings of the guide body are sealed with 3 stainless steel cover bands to protect the guide from splash water and dust. Alternatively, the opening can also be covered with a bellow or can be delivered without cover bands.

Fitting position: As required. Max. length 6.000 mm without joints.
Carriage mounting: By T-slots.
Unit mounting: By T-slots and mounting sets. The linear axis can be combined with any T-slot profile.
Belt type: HTD with steel reinforcement, no backlash when changing direction, repeatability ± 0,1 mm.
Carriage support: In the standard version, the carriage runs on 4 runner blocks which can be serviced at a central servicing position. For longer carriages the number of runner blocks can be increased.

Forces and torques



Size	120		160		200	
permitted dyn. Forces*	5000 km	10000 km	5000 km	10000 km	5000 km	10000 km
F_x (N)	894	800	1900	1800	4000	3800
F_y (N)	1776	1405	2236	1775	5155	4092
F_z (N)	2090	1650	5278	4189	11311	8977
M_x (Nm)	81	64	282	224	752	597
M_y (Nm)	97	77	283	225	813	646
M_z (Nm)	96	76	300	238	862	684
C (N)	2310		7800		22800	

All forces and torques related to the following:

existing values / table values

$$\frac{Fy}{Fy_{dyn}} + \frac{Fz}{Fz_{dyn}} + \frac{Mx}{Mx_{dyn}} + \frac{My}{My_{dyn}} + \frac{Mz}{Mz_{dyn}} \leq 1$$

	120	160	200
No-load torque			
Nm without cover bands	1,2	1,5	2,0
Nm with cover bands	1,6	2,1	4
Speed			
(m/s) max	5	5	5
Tensile force			
permanent (N)	900	1900	4000
0,2 s (N)	1000	2090	4300
Geometrical moments of inertia of aluminium profile			
I_x mm^4	5,61x10^5	2,13x10^6	4,81 x10^6
I_y mm^4	34,19x10^5	12,33x10^6	26,0 x10^6
Elastic modulus N/mm^2	70000	70000	70000

* referred to life-time

Formula: DSZ

Driving torque:

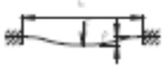
$$M_a = \frac{F*P*S_i}{2000*\pi} + M_{leer}$$

$$P_m = \frac{M_a*n}{9550}$$

F	= force	(N)
P	= pulley action perimeter	(mm)
S_i	= safety factor 1,2 ... 2	
M_{leer}	= no-load torque	(Nm)
n	= rpm pulley	(min^{-1})
M_a	= driving torque	(Nm)
P_m	= motor power	(KW)

Deflection:

$$f = \frac{F*L^3}{E*I*192}$$



f = deflection	(mm)
F = load	(N)
L = free length	(mm)
E = elastic modulus 70000	
I = second moment of area	(mm^4)

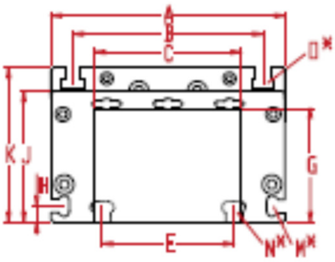
Nominal lifetime:

$$L = \left(\frac{C}{F}\right)^3 x10^5$$

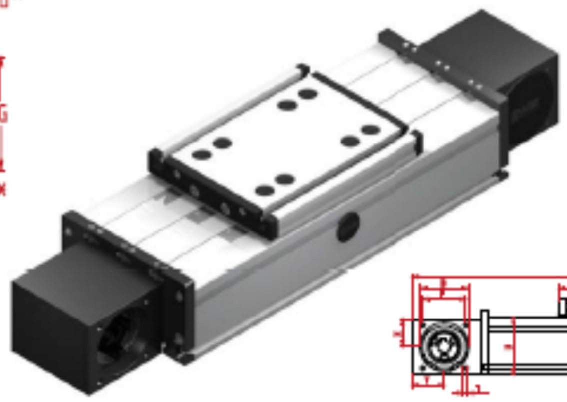
L	= Lifetime in meter	
C	= Dynamic load factor	(N)
F	= Middle load	(N)

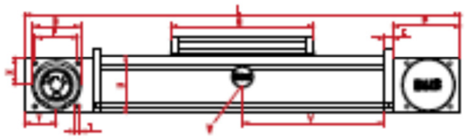
Positioning system DSZ 120, 160, 200

Dimensions (mm)



Increasing the carriage length will increase the basic length by the same amount.





*For slide nuts refer to chapter 2.2 page 2 V = Q + 100 mm W = servicing position

Size □	Basic length L	A	B	C	D	E	F	G	H	I	J	K	M for	N for	O for	P	Q	T	U	X	Y	Basic weight	Weight per 100 mm
DSZ 120	330	120	96	80	47	78	42	58	10	10	68	79	M 5	M 6	M 6	70	156	M 6	60	28	35	5,1 Kg	0,85 Kg
DSZ 160	440	160	130	100	68	90	60	78	11	12	90	106	M 6	M 8	M 8	95	200	M 8	80	39	45	12,0 kg	1,9 kg
DSZ 200	530	200	160	130	90	140	80	97	15	15	110	129	M 8	M 10	M 10	110	270	M 10	100	49	50	21,3 kg	2,9 kg

0 **Choice of guide body profile:**

(0) (1) (2) (3)

Internal profile with cover bands — Internal profile without cover bands — without internal profile and cover bands — with bellows

Stainless versions upon request.

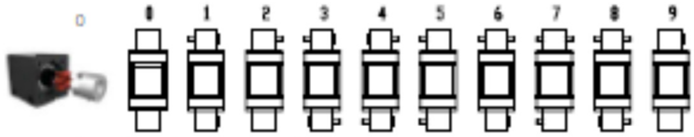
0 **Choice of carriages:**

(0) (1)

Size	Version 0		Version 1	
	Q	L	Q	L
120	156	330	156	330
160	200	440	>230	>470
200	270	530	>310	>570

0 **Drive version:**

0 1 2 3 4 5 6 7 8 9



9 is as 0, but with coupling claws on both sides.
The standard version is supplied without shaft. A shaft can be retrofitted by inserting it into the pulley bore and securing it with 2 locking rings or tension sets (size 200).

Belt table

Code No.		Size	Belt	mm/rev.	Number of teeth
0	**4**	**120**	5M25	130	26
0	**7**	**160**	8M30	176	22
0	**9**	**160**	8M50	176	22
0	**9**	**200**	8M50	224	28
1	**0**	**200**	8M70	224	28

Shaft dimensions

Size	Shaft ⌀ h6 x length	Key
120(5M25)	14 x 35	5x5x28
160(8M30)	18 x 45	6x6x40
160(8M50)	25 x 35	8x7x32
200(8M50)	22 x 45	6x6x40
200(8M70)	30 x 55	8x7x50

Basic length + stroke = total length

DSZ	160	1	0	0	0	0	7	1	01500
	Pos.	1	2	3	4	5	6	7	

Sample ordering code:
DSZ 160 with internal profile and cover bands, standard carriage, coupling claw on one side, 1060 mm stroke.

Appendix 8: Search of linear guidance systems

Typ vedení a výrobce	*Maximální rychlost přejezdu*	*Maximální délka lineárního vedení*	*Přesnost a opakovatelnost polohování*	*Nosnost a maximální zatížení vedení*
SPONA-ROL s.r.o. **Typ vedení: MONORACE**	8 m/s	4000 mm	Neuvedeno – dáno použitým pohonem	Axiálně: 6700 N Radiálně: 10700 N Moment Mx: 107,2 Nm
SPONA-ROL s.r.o. **Typ vedení: TWINRACE**	8 m/s	4000 mm	Eliminace chyb rovnoběžnosti v montáži díky 1 plovoucímu jezdci a 1 pevnému.	Axiálně: 27000 N Radiálně: 10800 N Moment Mz: 410 Nm
Fluid technik Bohemia **Elektrický pohon ODS – Origa drive system**	3 – 5 m/s Zrychlení do 50 ms-2	4000 mm	± 0,05 mm/m precizní přesnost polohování i při velké dynamické zátěži	F = 10000 N M = 950 Nm
Fluid technik Bohemia **Elektrický pohon - konstrukční řada OSP-E..BHD II**	do 5 m/s (do 10 m/s na vyžádání) Zrychlení do 50 ms-2	volitelně, do 5700 mm	± 0,05 mm/m	Axiálně: 15000 N Radiálně: 12000 N Moment Mz: 2500 Nm Moment My: 1800 Nm
Güdel **monoROll (type F or L)**	20 m/s Zrychlení do 100 ms-2	6000 mm	± 1.5mm	Axiálně: 2000 N Radiálně: 1000 N Moment Mz: Velmi vysoký 20x10^7 Nm
Raveo **BAHR modultechnik DLM 200**	6 m/s	6000 mm	± 0,05 mm	Axiálně: 13800 N Radiálně: 1200 N Moment Mz: 170 Nm Moment My: 420 Nm

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Typ vedení a výrobce	*Typ pohonů a převodů*	*Valivé tělíska a typ ložiska*	*Materiály vedení*
SPONA-ROL s.r.o. **Typ vedení: MONORACE**	Dle možnosti – ozubený řemen na vozíku nebo alternativně	Předepnuté kladičkové vedení se 3 či 5 kladkami MR43 a jednořadými kuličkovými ložisky. Tělo jezdce galvanicky pozinkováno.	Zakalená ocel tažená za studena. Superfinišované vodící plochy nízkoteplotní nitridací.
SPONA-ROL s.r.o. **Typ vedení: TWINRACE**	Dle možnosti – ozubený řemen na vozíku nebo alternativně	Vhodnost 5 kladiček. Dvouřadé kuličkové ložiska. Tělo jezdce galvanicky pozinkováno.	Zakalená ocel tažená za studena. Superfinišované vodící plochy nízkoteplotní nitridací.
Fluid technik Bohemia **Elektrický pohon ODS – Origa drive system**	Pohon ozubeným řemenem ODS-B: volitelně do 4 - 6 m	Velikost profilu 145, 175, 225 mm. Robustní a tuhé těleso s integrovaným vedením tvoří samonosný rám integrované vedení s kuličkovými pouzdry.	Převážně hliníkové profily.
Fluid technik Bohemia **Elektrický pohon - konstrukční řada OSP-E..BHD II**	elektrický pohon s ozubeným řemenem a integrovaným vedením s kuličkovými pouzdry, planetová převodovka	• velmi precizní přesnost polohování • integrované vedení s kuličkovými pouzdry • velmi tichý chod	tvrzená ocelová vedení s vysokou přesností GKI, H Krycí pás z nerezu. Další komponenty ze slitiny hliníku.
Güdel **monoROll (type F or L)**	Motor se specifickou přírubou a převodovkou	Excentrické kladičky spolu s broušenými lištami připevněné na hliníkovém profilu.	Hliníkový profil
Raveo **BAHR modultechnik DLM 200**	Polohování obstarává lineární synchronní AC motor, který umožňuje přímočarý pohyb bez zprostředkujícího převodu.	Mechanický systém s jezdcem a dvojitým vnitřním rolničkovým vedením. Magnetická přitažlivost zapřičiňuje sílu mezi vedením a vozíkem s absencí proudu.	Hliníkové profily

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Typ vedení a výrobce	*Životnost a nutnost maziv, odolnost vůči chemikáliím a kyselinám*	*Vhodnost k vysokému napětí a teplotám*	*Poznámky + link k elektronickému odkazu katalogu:*
SPONA-ROL s.r.o. **Typ vedení: MONORACE**	Kladičky s tukovou náplní pro celou životnost. Samomazací systém.	-40°C až +120 °C Vhodnost k vysokému napětí neuvedena	http://www.spona-rol.cz/linearni_vedeni.htm
SPONA-ROL s.r.o. **Typ vedení: TWINRACE**	Kladičky s tukovou náplní pro celou životnost. Samomazací systém. Kompaktní jezdec.	-30°C až +80 °C Vhodnost k vysokému napětí neuvedena	http://www.spona-rol.cz/linearni_vedeni.htm
Fluid technik Bohemia **Elektrický pohon ODS – Origa drive system**	Centrální mazání.	-20°C až +80 °C Vhodnost k vysokému napětí neuvedena	možnost doplnění tlumičů rázů a odměřovacího systému. http://www.fluidbohemia.cz/
Fluid technik Bohemia **Elektrický pohon - konstrukční řada OSP-E..BHD II**	ocel se systémem stírání, maznička, třída předpětí 0,02×C	-30°C až +80 °C Vhodnost k vysokému napětí neuvedena	http://www.fluidbohemia.cz/resources/upload/data/320_1.15.002CZ.pdf
Güdel **monoROll (type F or L)**	Olejové mazání se speciálním stíráním a možností doplnění lubrikantu.	Neuvedeno Vhodnost k vysokému napětí neuvedena	http://www.gudel.com/cz/components/#home_top-anchor
Raveo **BAHR modultechnik DLM 200**	Bez mazání	Neuvedeno Vhodnost k vysokému napětí neuvedena	http://raveo.cz/motor_lin možnost pohánět více vozíků nezávisle na sobě